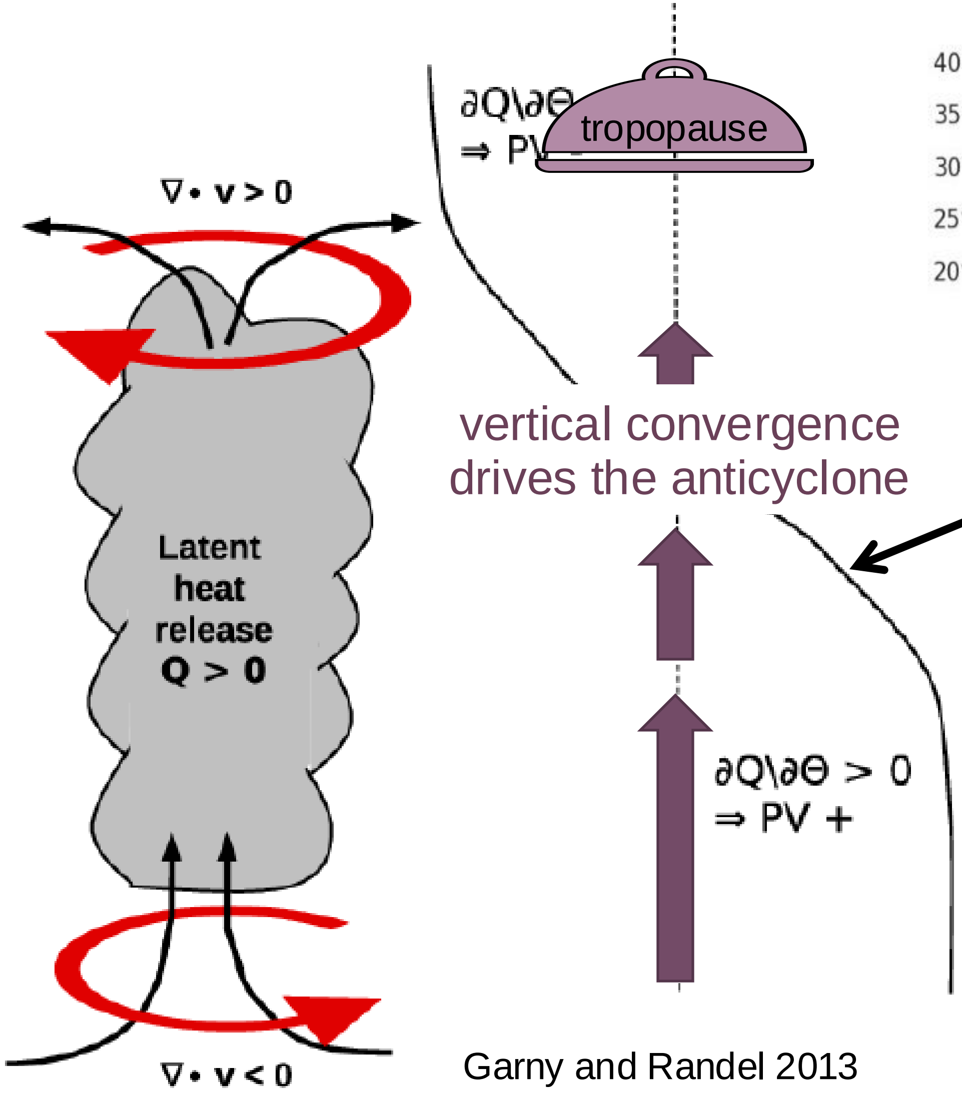
CLIMATOLOGY AND VARIABILITY OF WATER VAPOUR IN THE ASIAN MONSOON TROPOPAUSE LAYER

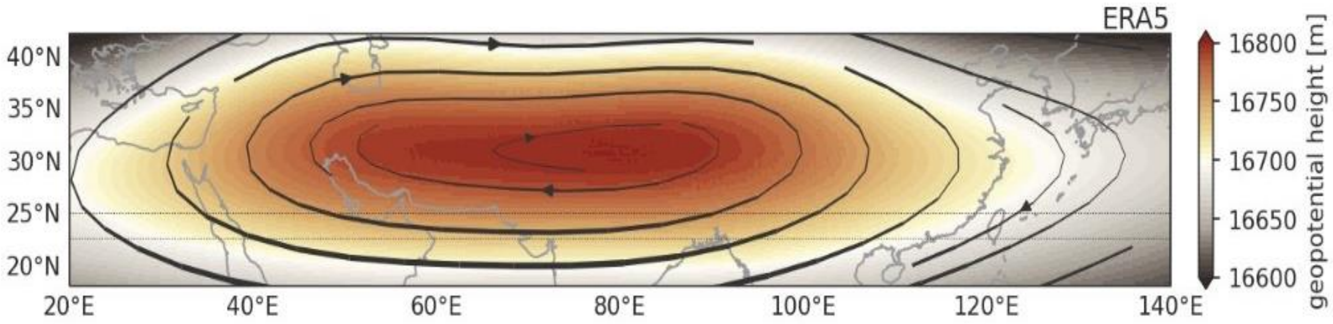
Jonathon S. Wright, Shenglong Zhang, and Jiao Chen
Tsinghua University Department of Earth System Science

With thanks to:
Sean Davis, Masatomo Fujiwara, Jie Gao, Paul Konopka, Mengqian Lu, Gloria Manney, Susann Tegtmeier, Xiaolu Yan, Guang Zhang, Nuanliang Zhu

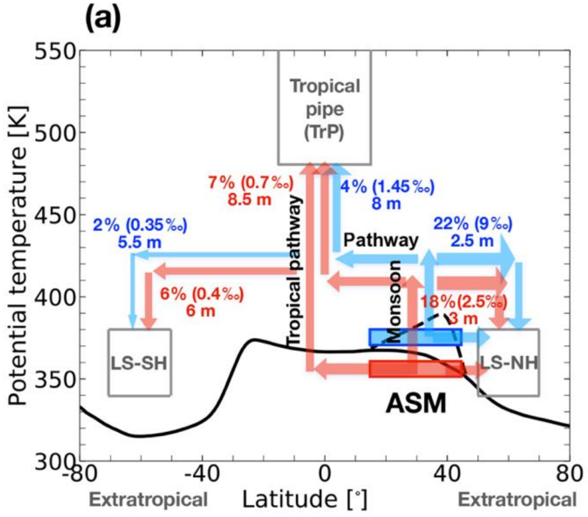
ASIAN MONSOON ANTICYCLONE: CIRCULATION



Garny and Randel 2013



Strength of vertical convergence / horizontal divergence depends on how sharply the 'brake' is applied

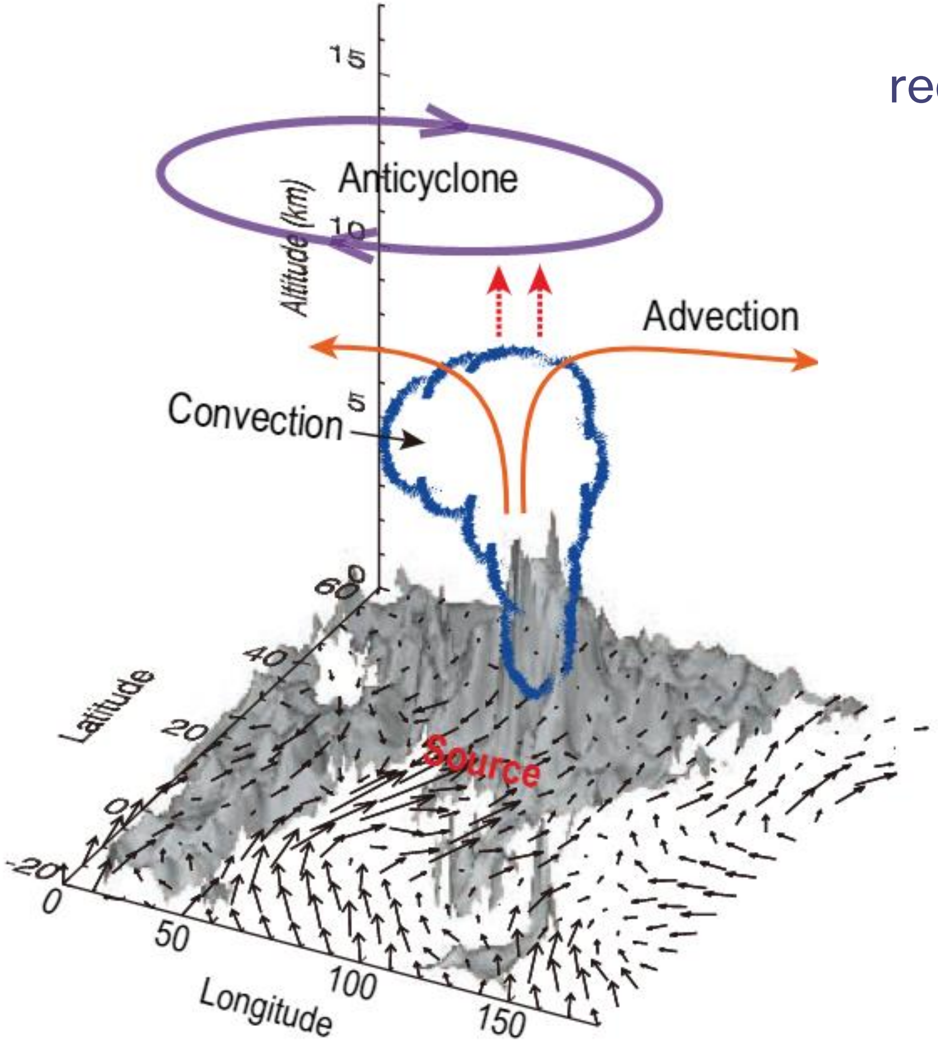


An influential pathway to the global stratosphere

Yan et al. 2019

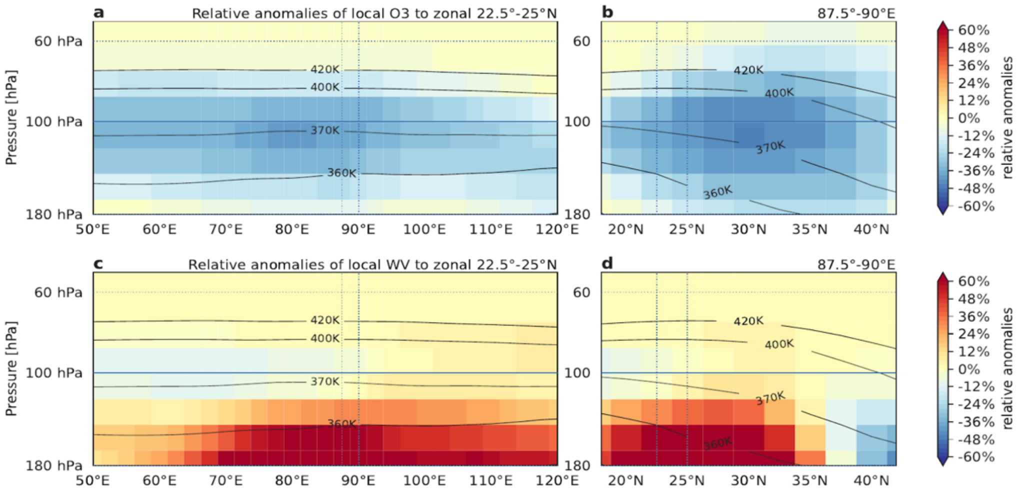
ASIAN MONSOON ANTICYCLONE: COMPOSITION

Gao et al. 2023

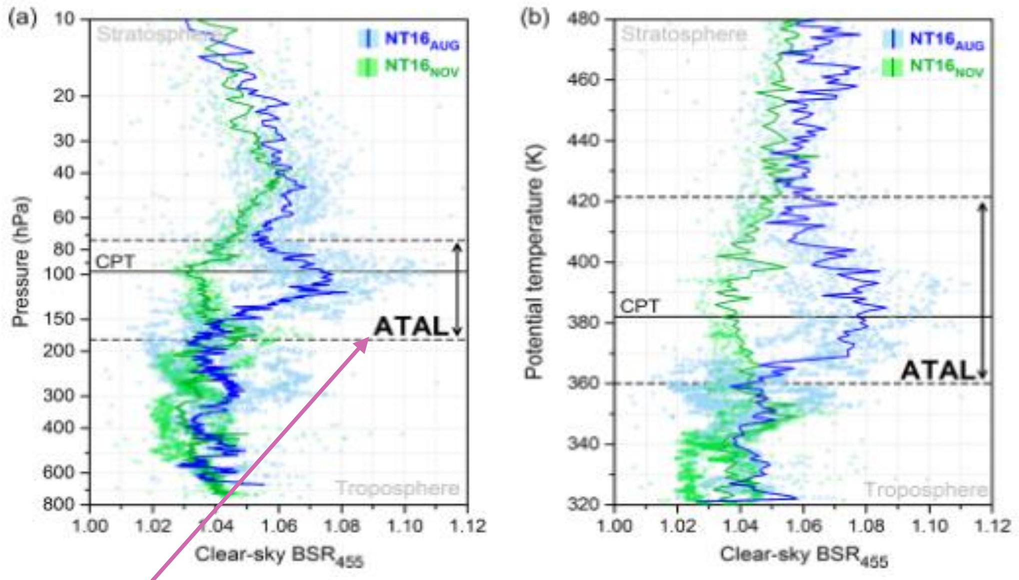


reduced ozone

abundant wv



polluted air

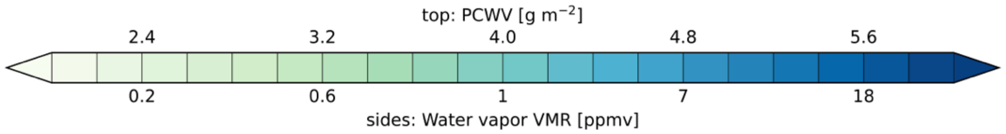


Bian et al. 2020

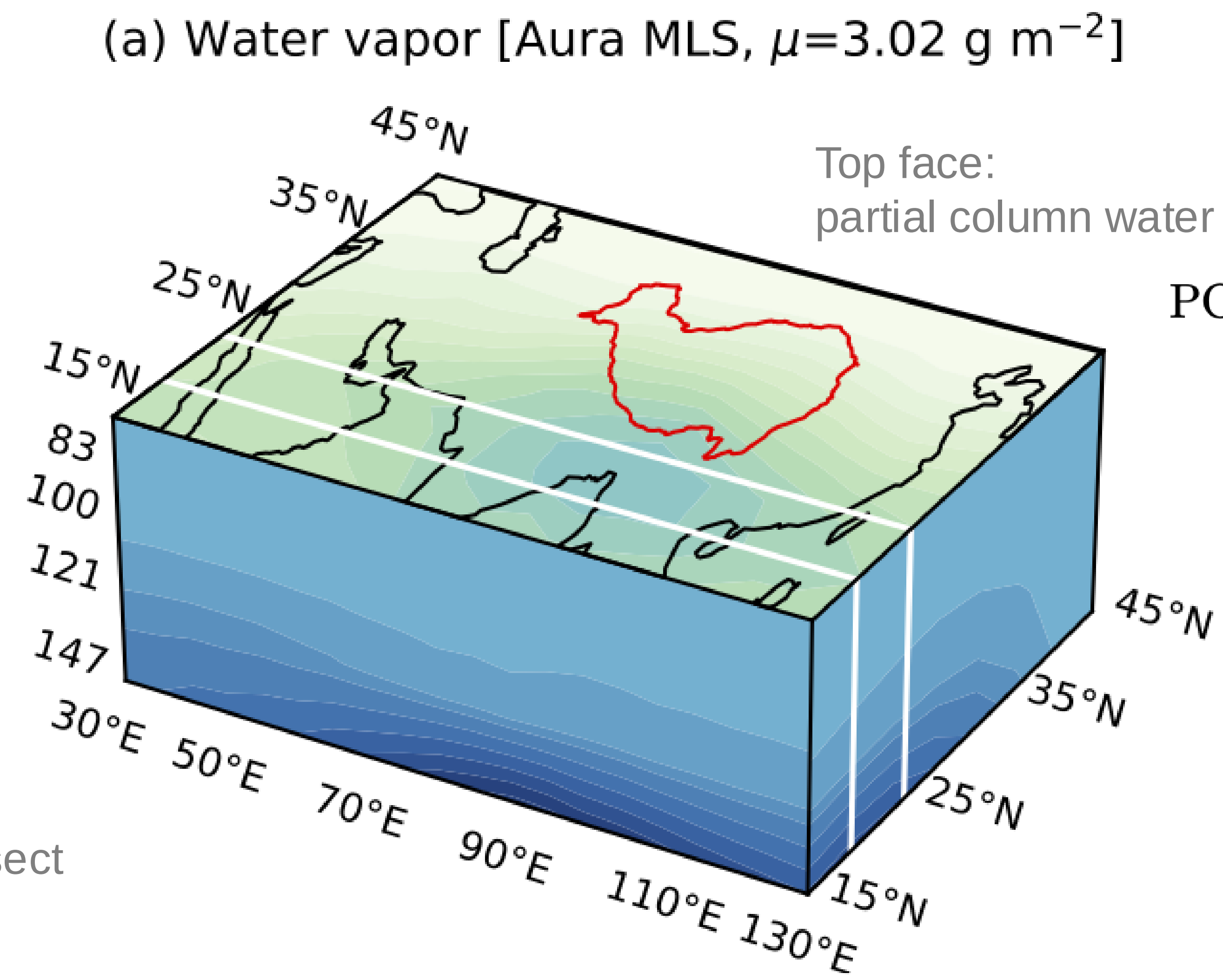
“Asian tropopause aerosol layer”

Hanumanthu et al. 2016

OBSERVATIONS: AURA MLS



May–September
2005–2021



Top face:
partial column water vapor

68 hPa

$$\mathrm{PCWV} = -\frac{1}{g}\int_{p_{\mathrm{bot}}}^{p_{\mathrm{top}}} q\,dp$$

147 hPa

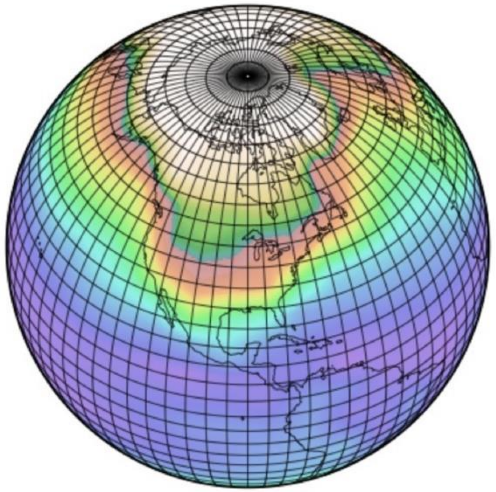
East face:
zonal mean across
30-130E

South face:
east-west transect
within 20-25N

ATMOSPHERIC REANALYSIS PRODUCTS

Component 1: a global atmospheric model

Usually a well-tested earlier version of an operational weather forecast model



	Name	Centre	DAS	Grid	Levels	Freq	Chem
Chemical reanalysis	CAMS	ECMWF	IFS 4DVar	~79km	60 to 10Pa	3h	IFS(CB05)
Meteorological reanalyses	ERA5	ECMWF	IFS 4DVar	~31km	137 to 1Pa	1h	none
	JRA-3Q	JMA	JMA 4DVar	~40km	100 to 1Pa	6h	none
	MERRA-2	GMAO	IAU	~60km	72 to 1Pa	3h	none
Chemical reanalysis	M2-SCREAM	GMAO	CoDAS + replay	~60km	72 to 1Pa	3h	StratChem

ATMOSPHERIC REANALYSIS PRODUCTS

Water vapor observations are assimilated…

ERA5 & CAMS
Up to tropopause

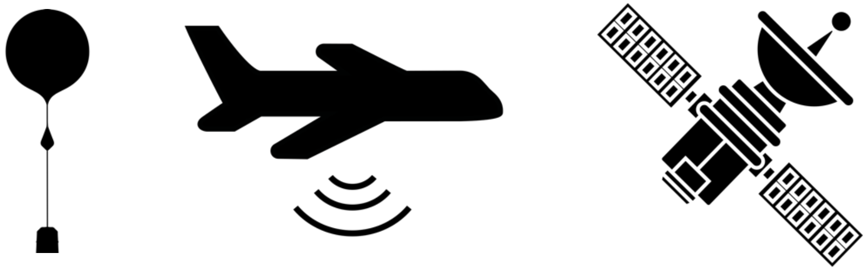
JRA-3Q
Up to 100 hPa

MERRA-2
Up to 300 hPa

M2-SCREAM
Assimilates Aura MLS v4

Component 2: input observations

From radiosondes, aircraft, satellites, etc.



ATMOSPHERIC REANALYSIS PRODUCTS

Water vapor observations are assimilated…

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Up to tropopause

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Up to 100 hPa

MERRA-2
Up to 300 hPa

M2-SCREAM
Assimilates Aura MLS v4

Assimilation increments in UTLS WV are…

ERA5 & CAMS
Suppressed above the tropopause

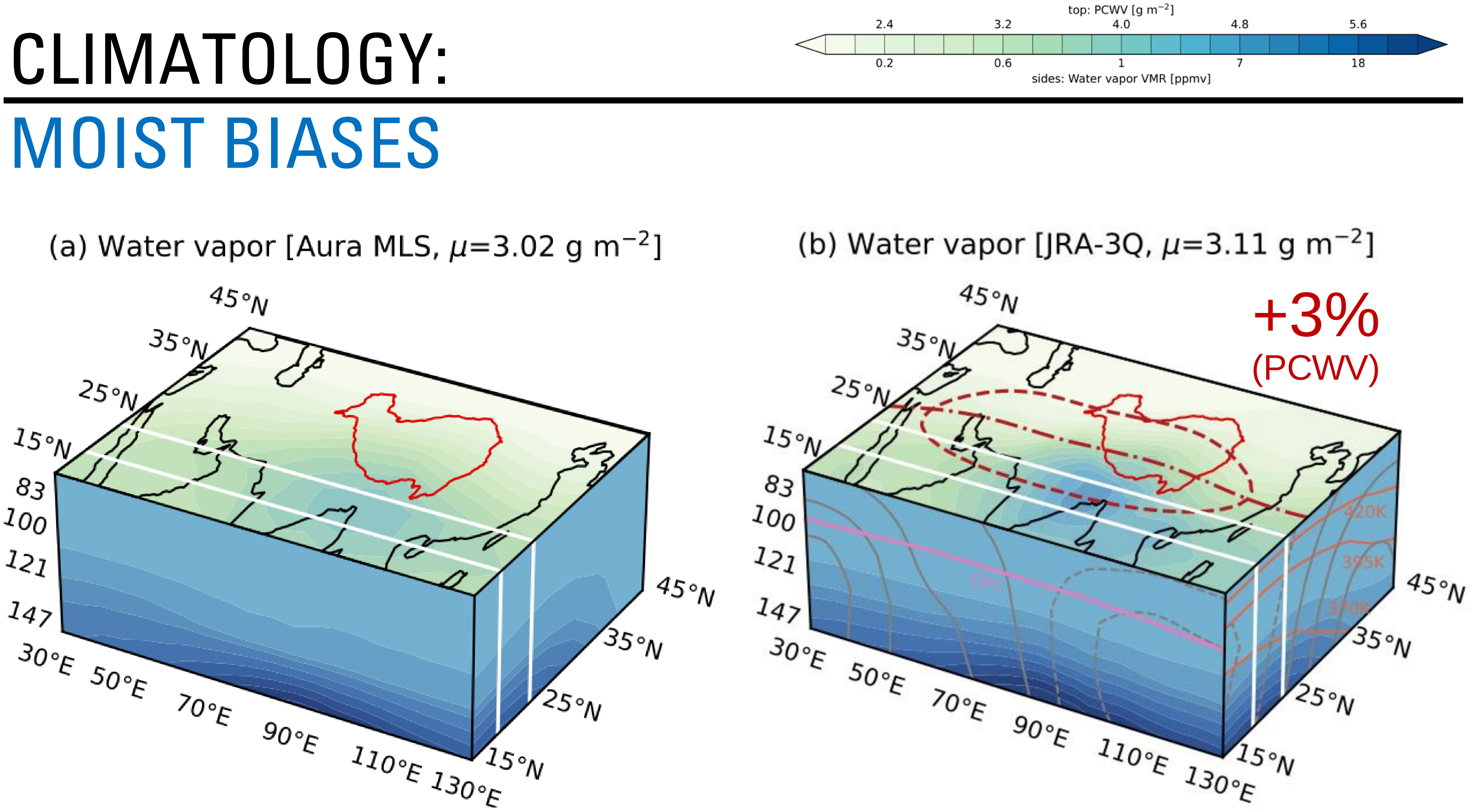
JRA3Q & MERRA-2
Not suppressed (but MERRA-2 relaxes stratospheric water vapor to a climatology, damping variability above the tropopause)

Component 3: a data assimilation system

Combines the model-generated background state (defined everywhere) with available observations (point locations in space and time), considering uncertainties and errors in both

CLIMATOLOGY:

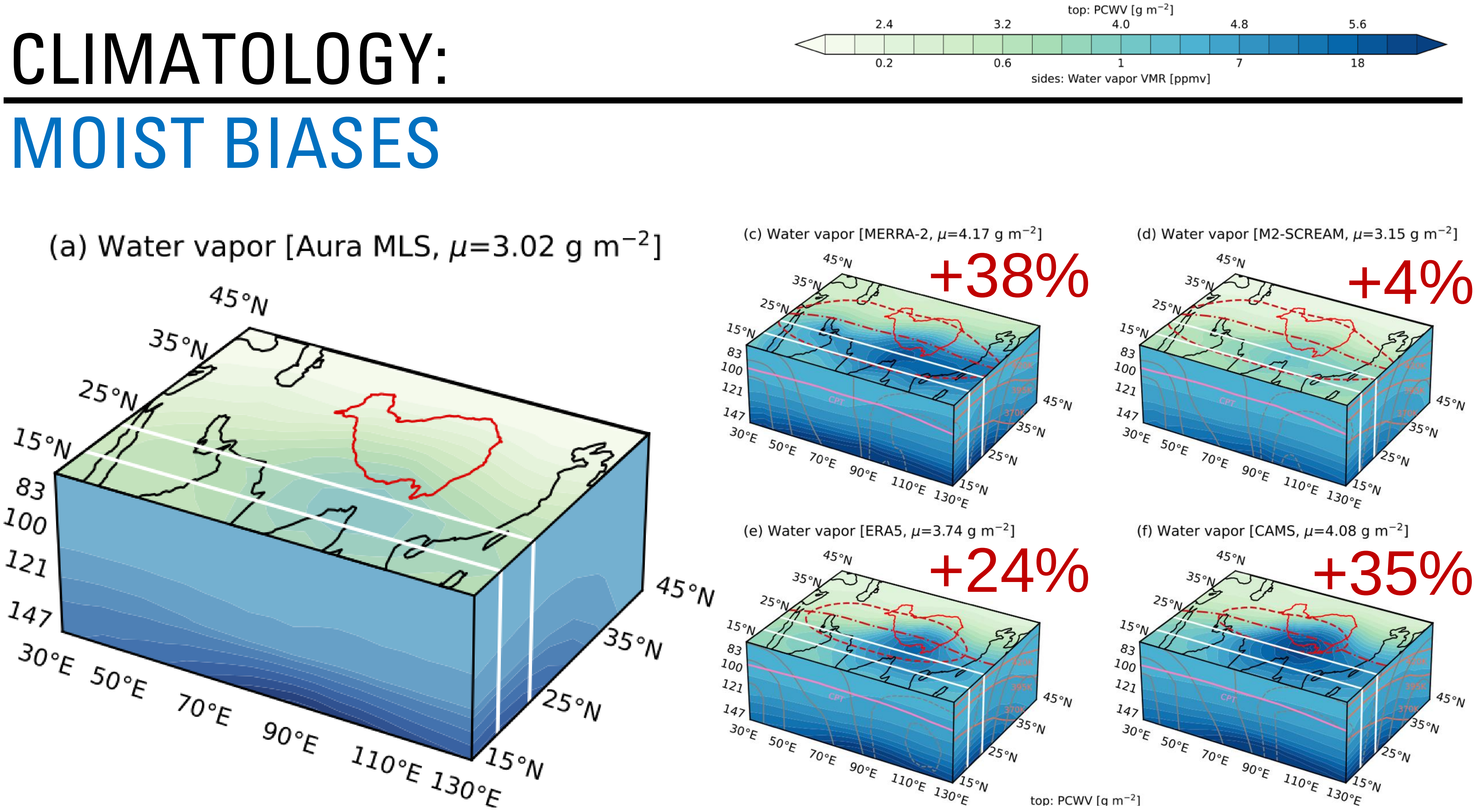
MOIST BIASES



Dashed contour: Montgomery streamfunction @ 395K

CLIMATOLOGY:

MOIST BIASES

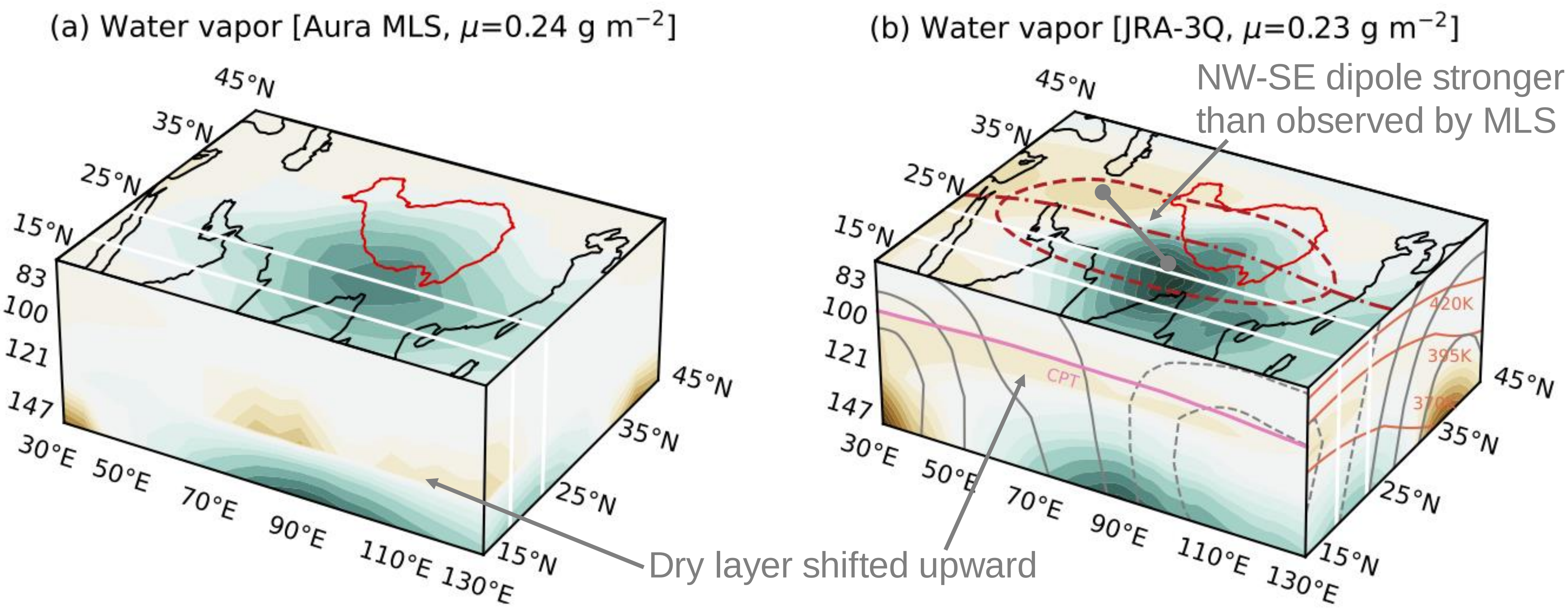


Dashed contour: Montgomery streamfunction @ 395K

CLIMATOLOGY:

Note: no weighting functions have been applied

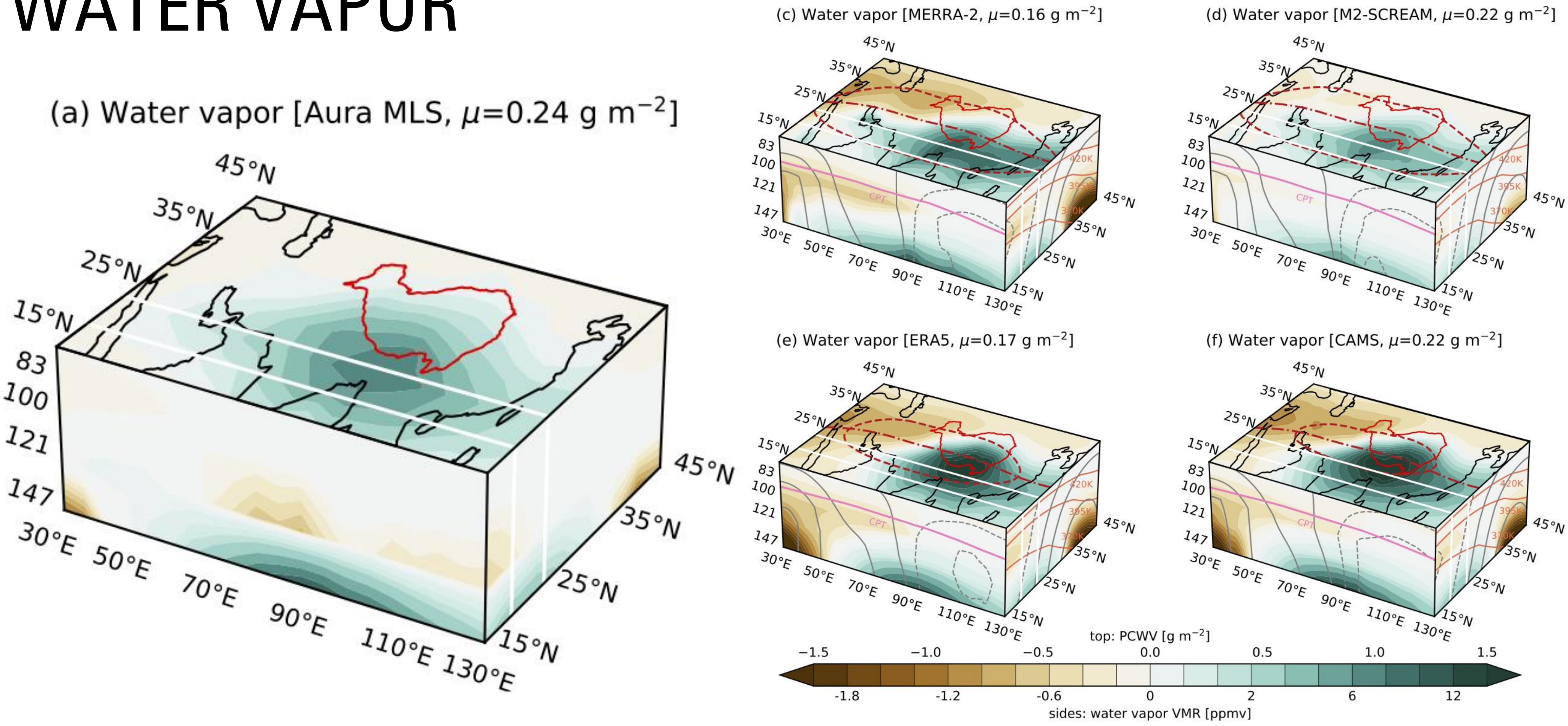
REGIONAL ANOMALIES WELL REPRODUCED



Regional distribution after subtracting the global zonal mean

CLIMATOLOGY: WATER VAPOR

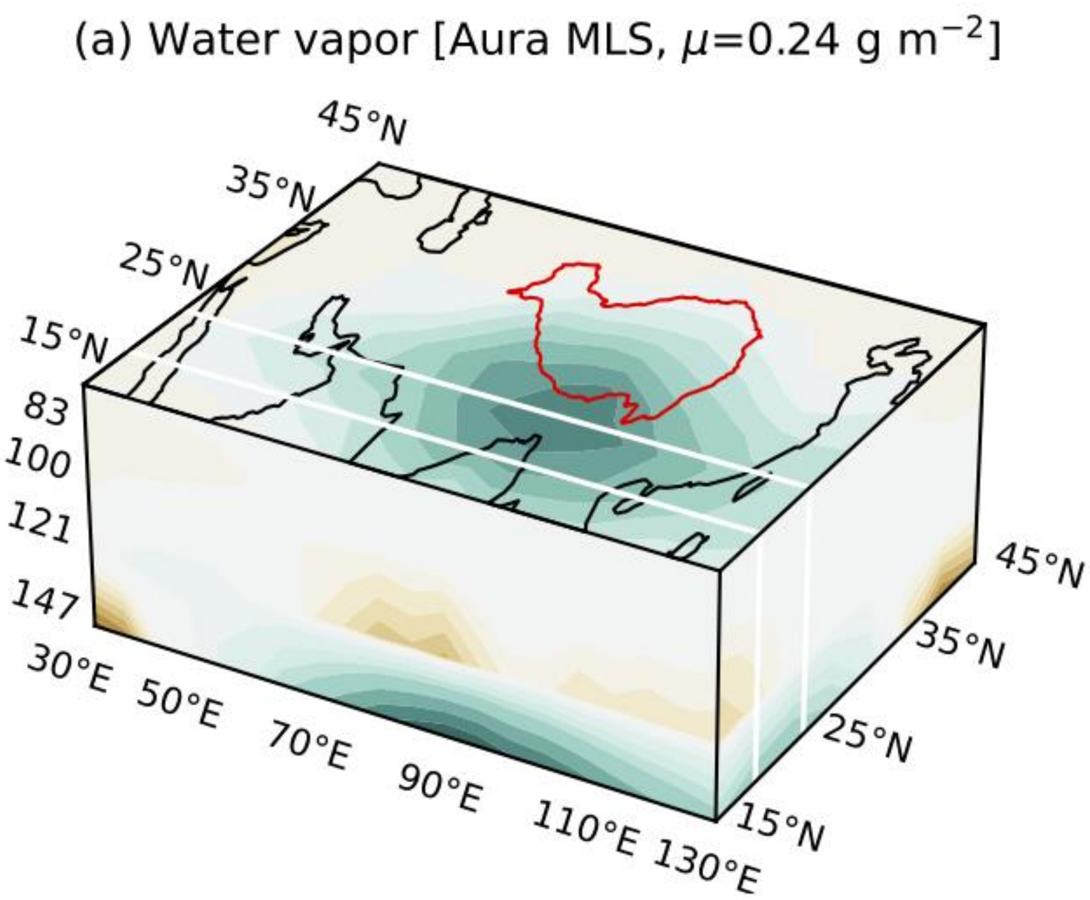
Note: no weighting functions have been applied

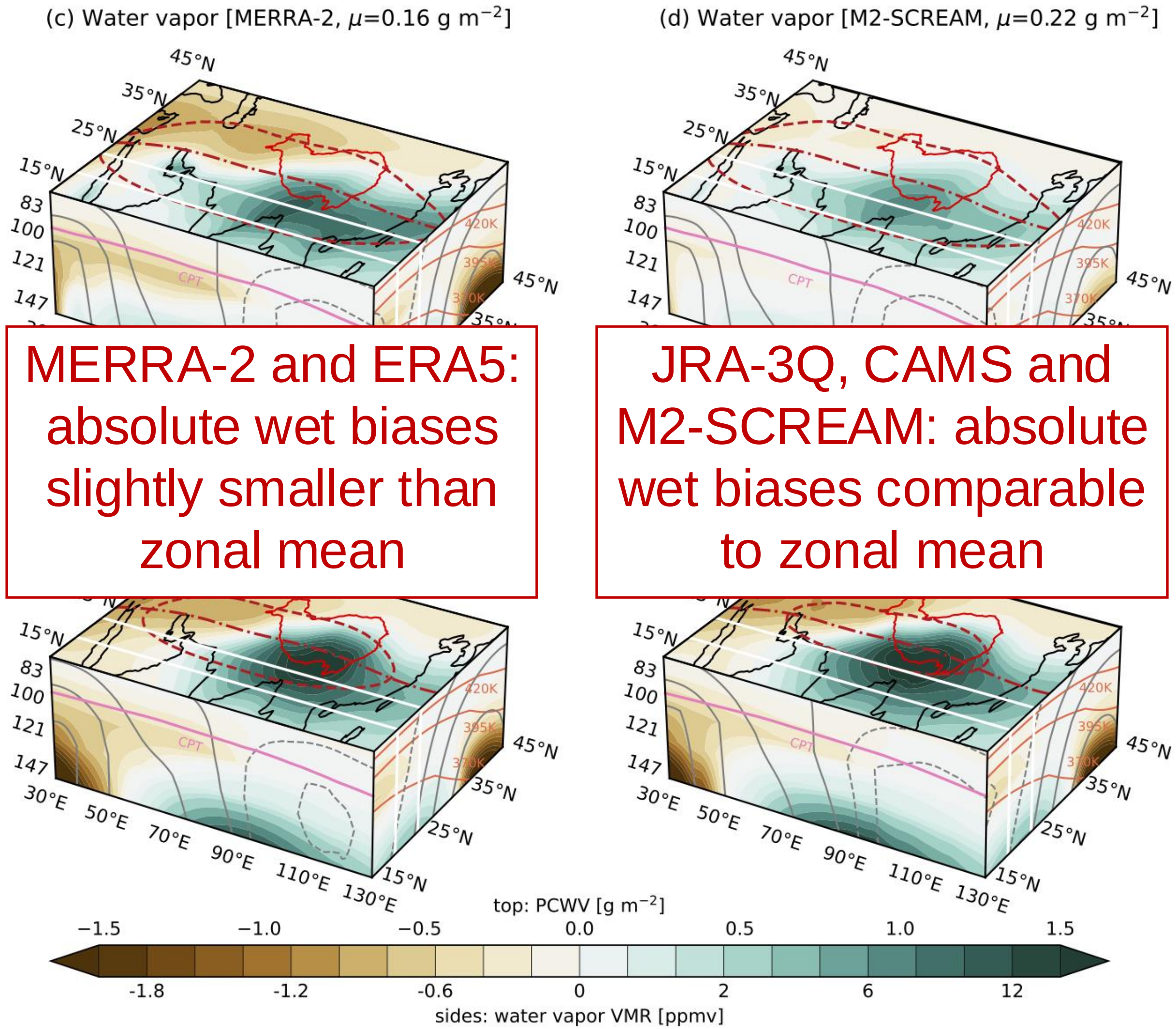


Regional anomalies relative to global zonal mean

CLIMATOLOGY: WATER VAPOR

Note: no weighting functions have been applied





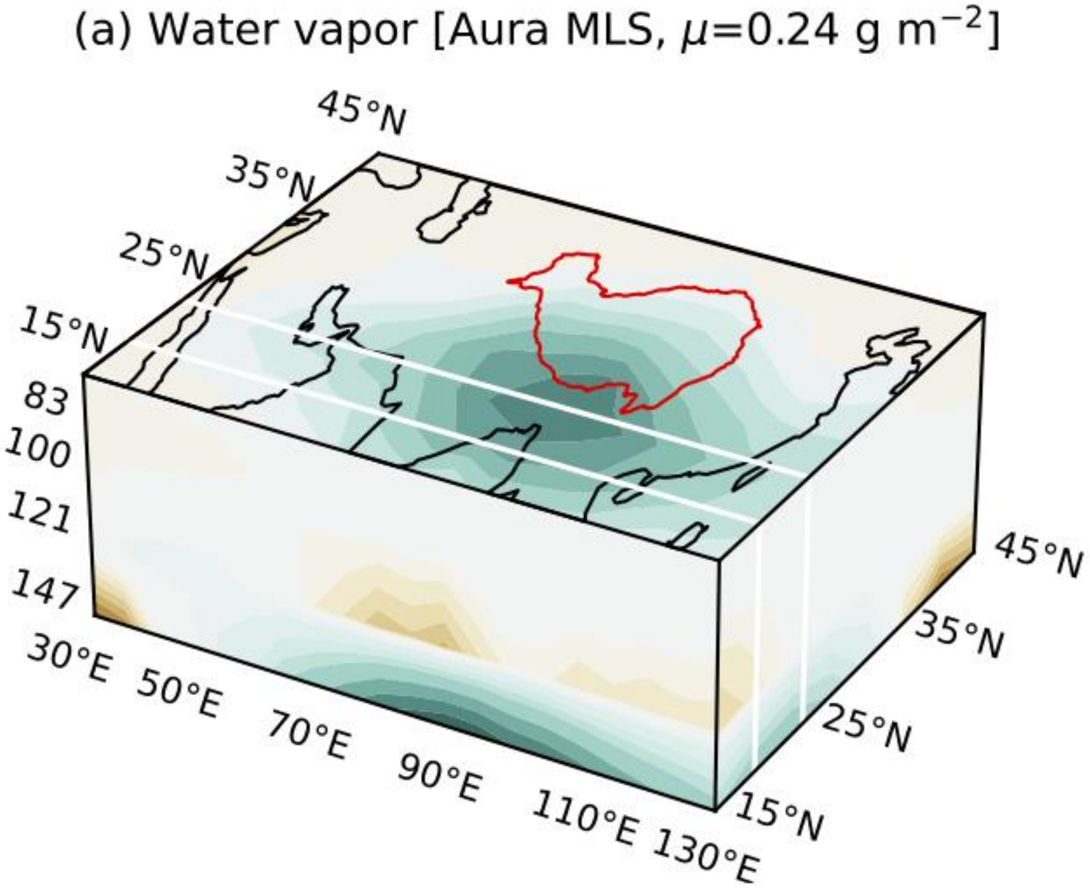
MERRA-2 and ERA5: absolute wet biases slightly smaller than zonal mean

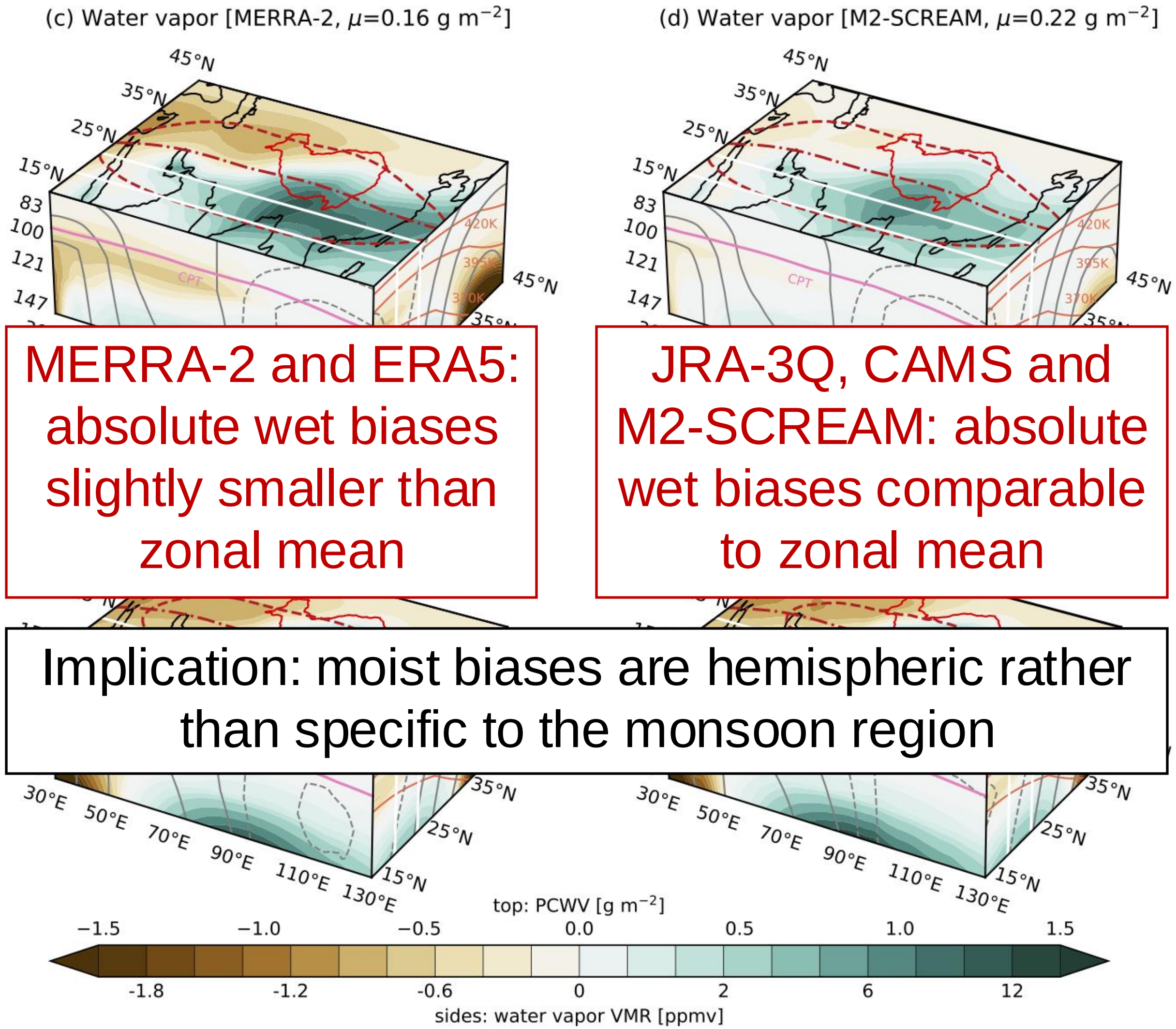
JRA-3Q, CAMS and M2-SCREAM: absolute wet biases comparable to zonal mean

Regional anomalies relative to global zonal mean

CLIMATOLOGY: WATER VAPOR

Note: no weighting functions have been applied





MERRA-2 and ERA5: absolute wet biases slightly smaller than zonal mean

JRA-3Q, CAMS and M2-SCREAM: absolute wet biases comparable to zonal mean

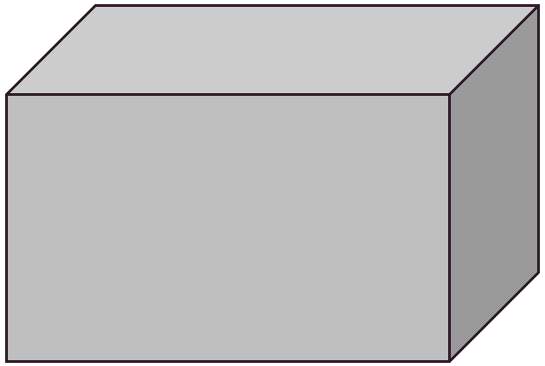
Implication: moist biases are hemispheric rather than specific to the monsoon region

Regional anomalies relative to global zonal mean

CLIMATOLOGY:

BUDGETS

$$\frac{\partial q}{\partial t} + \nabla \cdot (\mathbf{V} q) + \frac{\partial (\omega q)}{\partial p} = S_{\mathrm{phy}} + S_{\mathrm{asm}} + S_{\mathrm{res}}$$

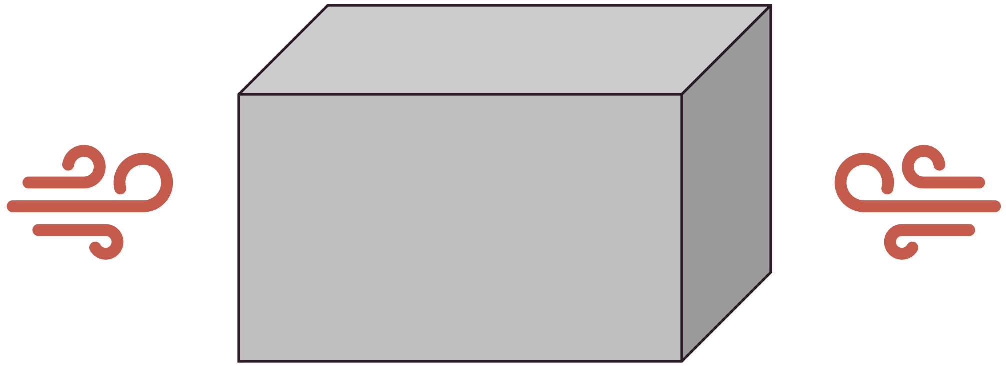


In a reanalysis grid cell, changes result from

CLIMATOLOGY:

BUDGETS

$$\frac{\partial q}{\partial t} + \nabla \cdot (\mathbf{V}q) + \frac{\partial(\omega q)}{\partial p} = S_{\mathrm{phy}} + S_{\mathrm{asm}} + S_{\mathrm{res}}$$



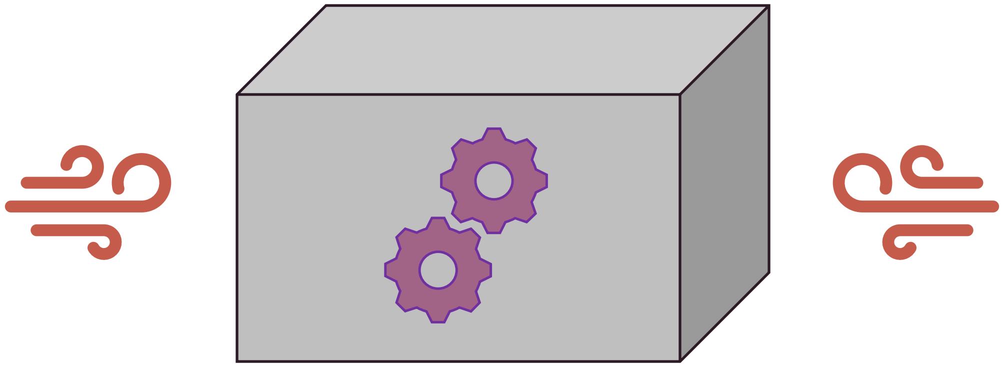
In a reanalysis grid cell, changes result from

- Dynamics (resolved advective transport into and out of the cell)

CLIMATOLOGY:

BUDGETS

$$\frac{\partial q}{\partial t} + \boxed{\nabla \cdot (\mathbf{V} q) + \frac{\partial(\omega q)}{\partial p}} = \boxed{S_{\mathrm{phy}}} + S_{\mathrm{asm}} + S_{\mathrm{res}}$$



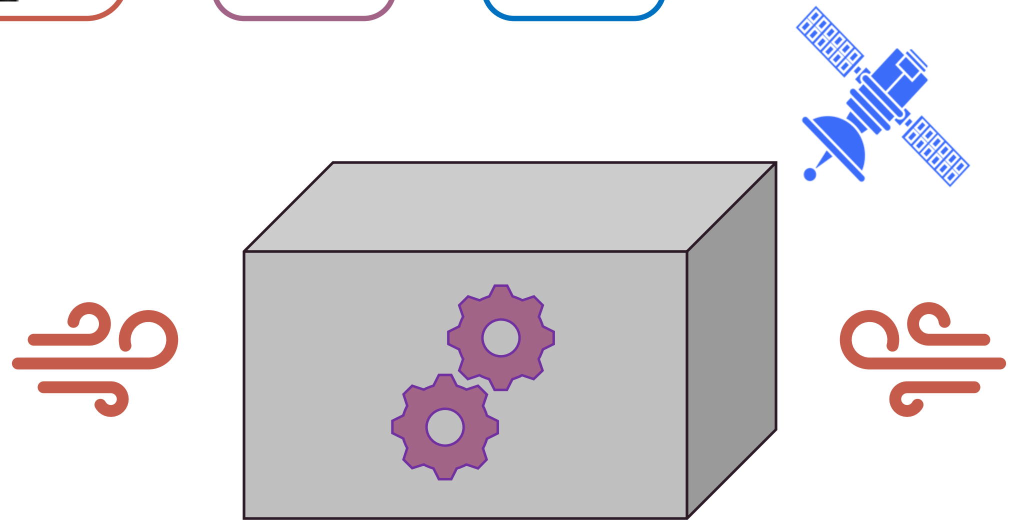
In a reanalysis grid cell, changes result from

- Dynamics (resolved advective transport into and out of the cell)
- Physics (processes smaller than the cell: radiation, turbulence, clouds...)

CLIMATOLOGY:

BUDGETS

$$\frac{\partial q}{\partial t} + \nabla \cdot (\mathbf{V}q) + \frac{\partial(\omega q)}{\partial p} = S_{\mathrm{phy}} + S_{\mathrm{asm}} + S_{\mathrm{res}}$$



In a reanalysis grid cell, changes result from

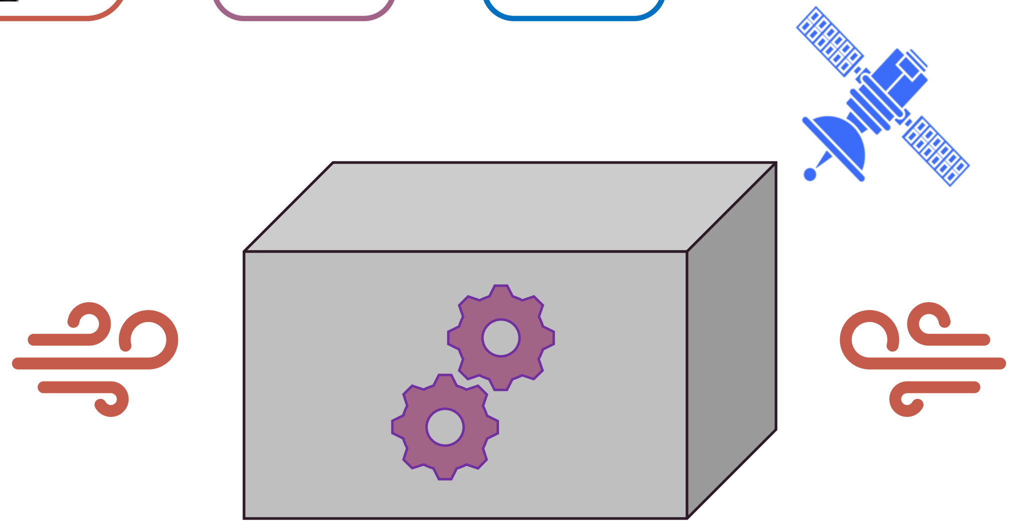
- Dynamics (resolved advective transport into and out of the cell)
- Physics (processes smaller than the cell: radiation, turbulence, clouds...)
- Data assimilation (adjustment to match available observations)

CLIMATOLOGY:

BUDGETS

$$\frac{\partial q}{\partial t} + \nabla \cdot (\mathbf{V} q) + \frac{\partial(\omega q)}{\partial p} = S_{\text{phy}} + S_{\text{asm}} + S_{\text{res}}$$

Belongs to dynamics in this formulation



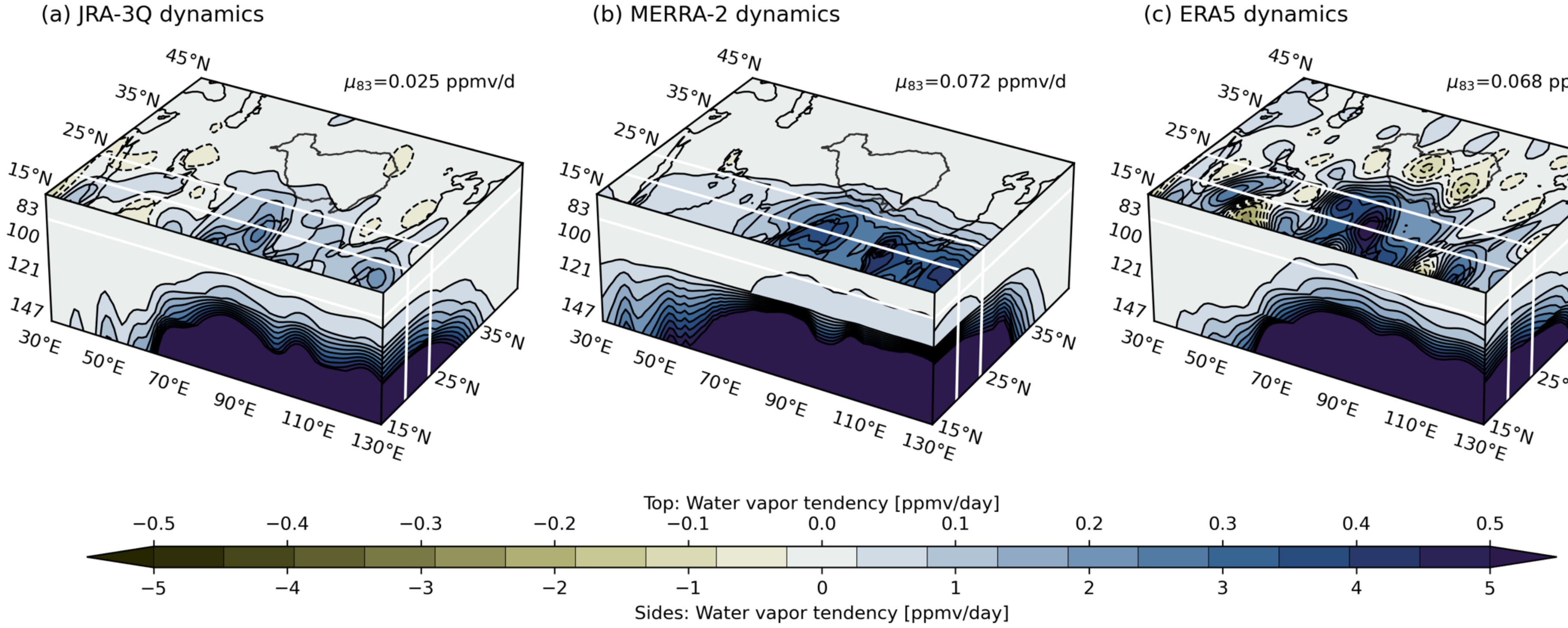
In a reanalysis grid cell, changes result from

- Dynamics (resolved advective transport into and out of the cell)
- Physics (processes smaller than the cell: radiation, turbulence, clouds...)
- Data assimilation (adjustment to match available observations)

CLIMATOLOGY:

BUDGETS: DYNAMICS (FLUX CONVERGENCE)

$$\frac{\partial q}{\partial t} + \boxed{\nabla \cdot (\mathbf{V} q) + \frac{\partial (\omega q)}{\partial p}} = S_{\mathrm{phy}} + S_{\mathrm{asm}} + S_{\mathrm{res}}$$

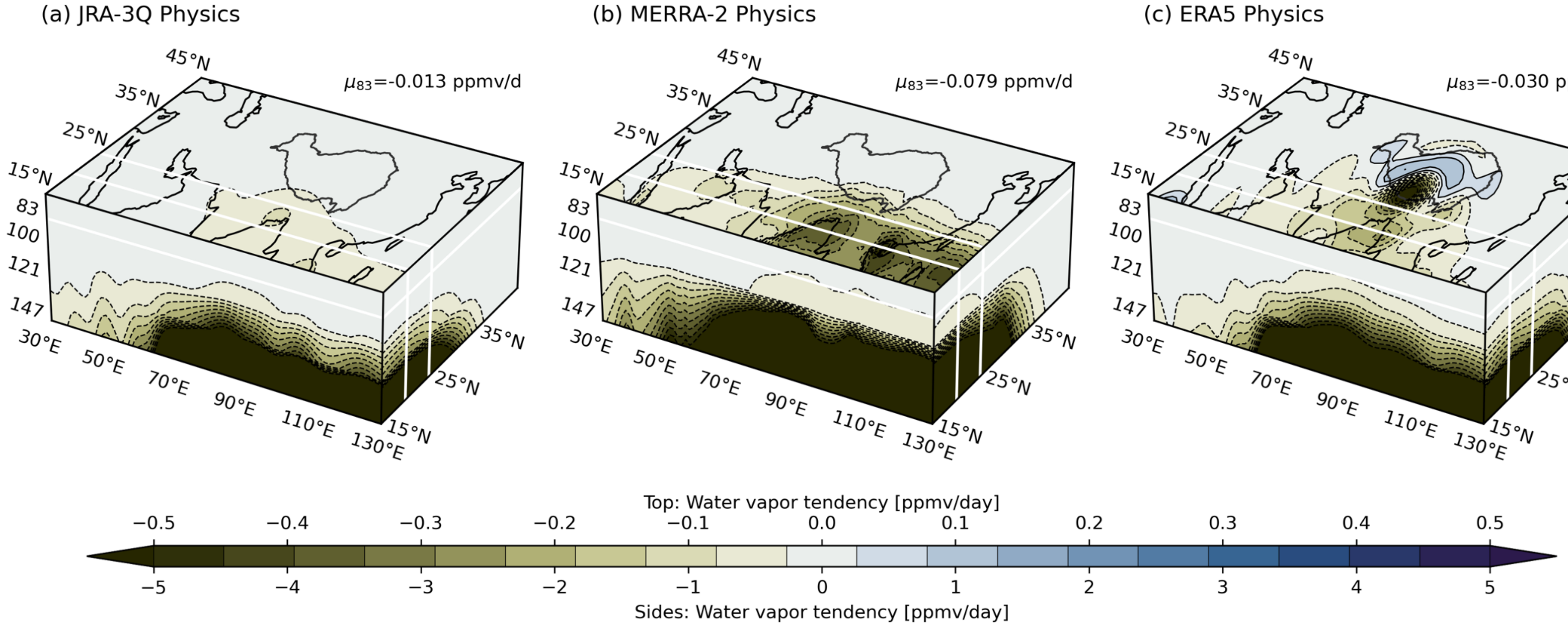


The dynamics term includes vertical (moistening in the east: moisture convergence) and horizontal (drying in the east: moisture divergence) advective components

CLIMATOLOGY:

BUDGETS: PARAMETERIZED PHYSICS

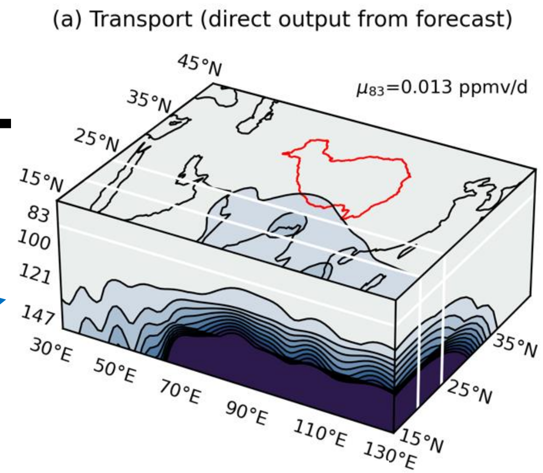
$$\frac{\partial q}{\partial t} + \nabla \cdot (\mathbf{V}q) + \frac{\partial(\omega q)}{\partial p} = S_{\text{phy}} + S_{\text{asm}} + S_{\text{res}}$$



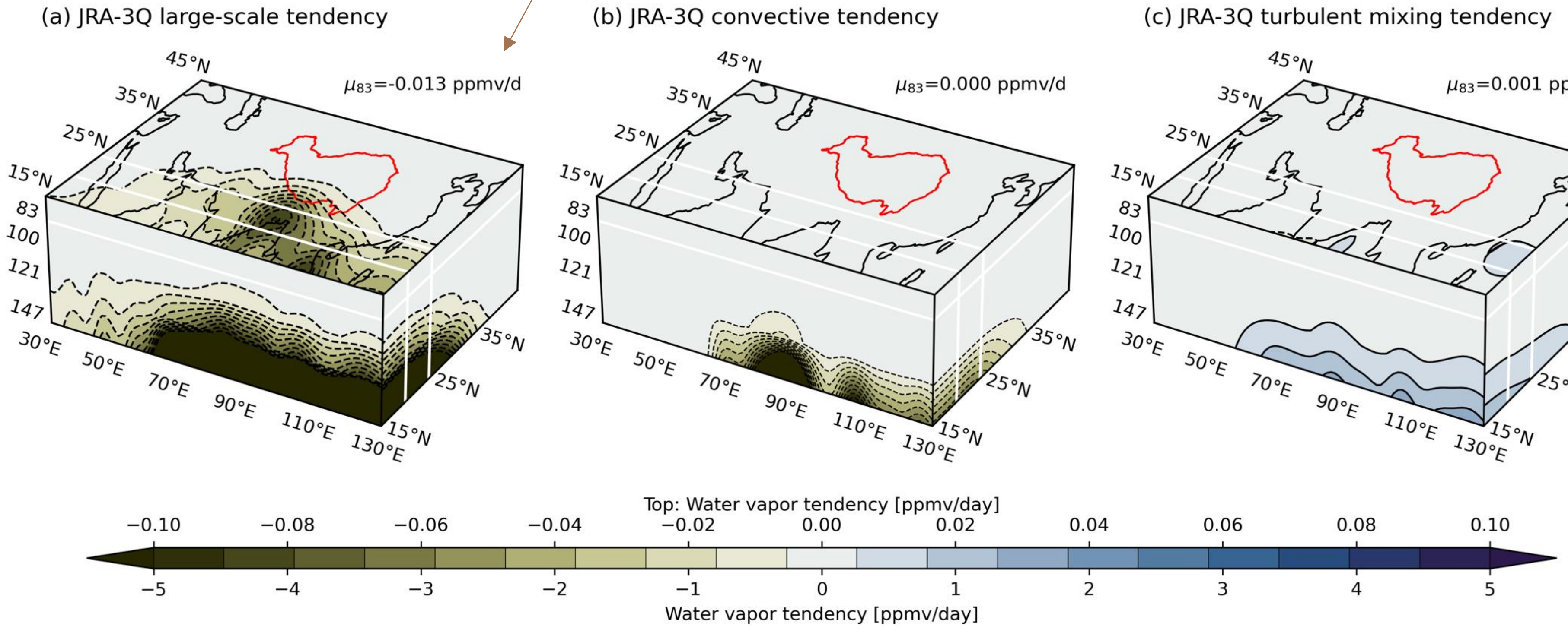
The physics term includes effects of parameterized convection, large-scale condensation, and turbulent mixing

CLIMATOLOGY:

BUDGETS: DOMINANT BALANCE



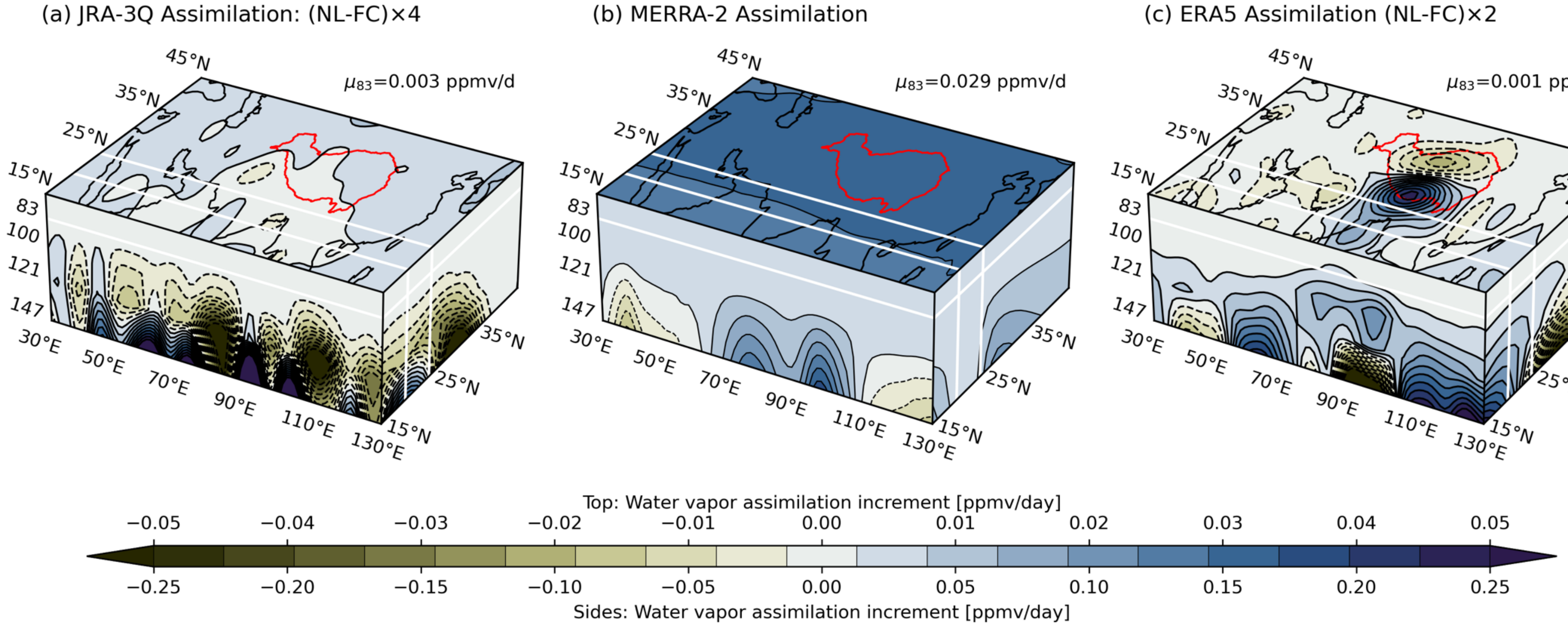
The dominant balance is between advective moistening (right) and condensation drying (below): advection–condensation



CLIMATOLOGY:

BUDGETS: DATA ASSIMILATION

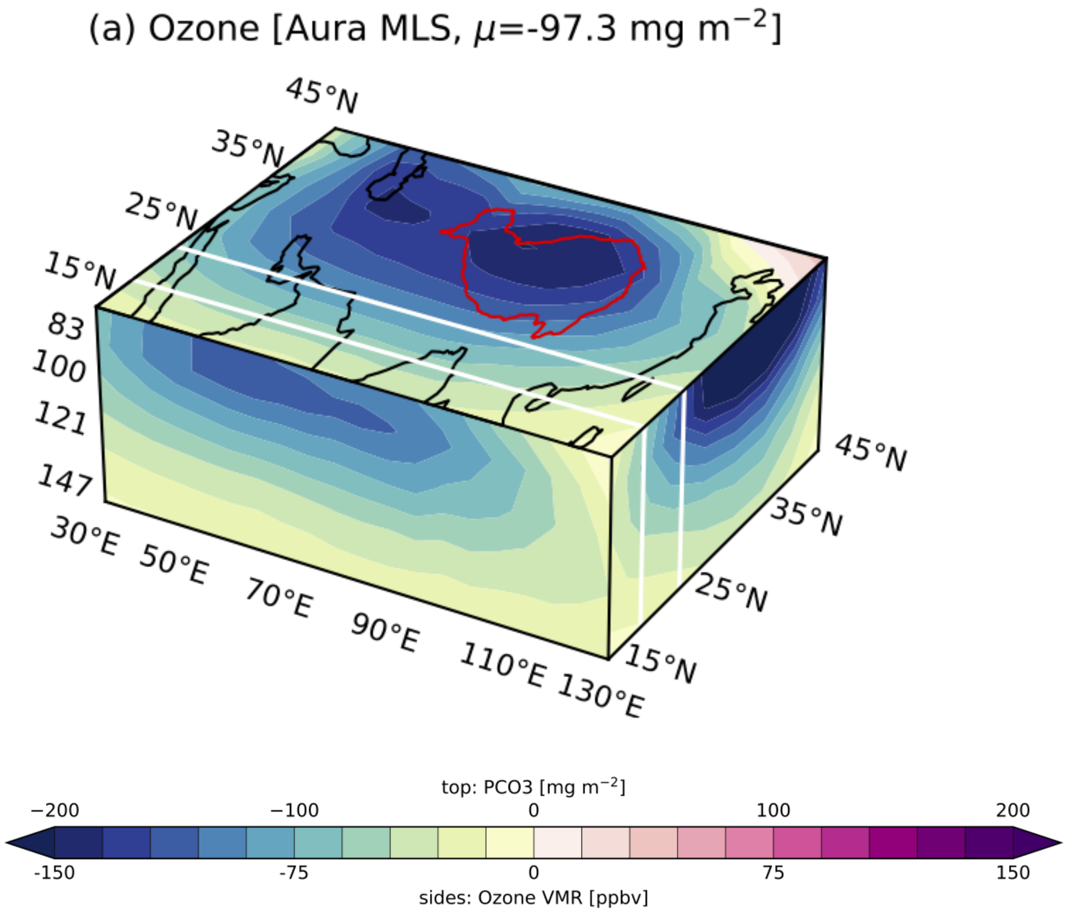
$$\frac{\partial q}{\partial t} + \nabla \cdot (\mathbf{V} q) + \frac{\partial (\omega q)}{\partial p} = S_{\text{phy}} + S_{\text{asm}} + S_{\text{res}}$$



The data assimilation term is smaller than dynamics or physics but comparable to the balance

CLIMATOLOGY:

OZONE

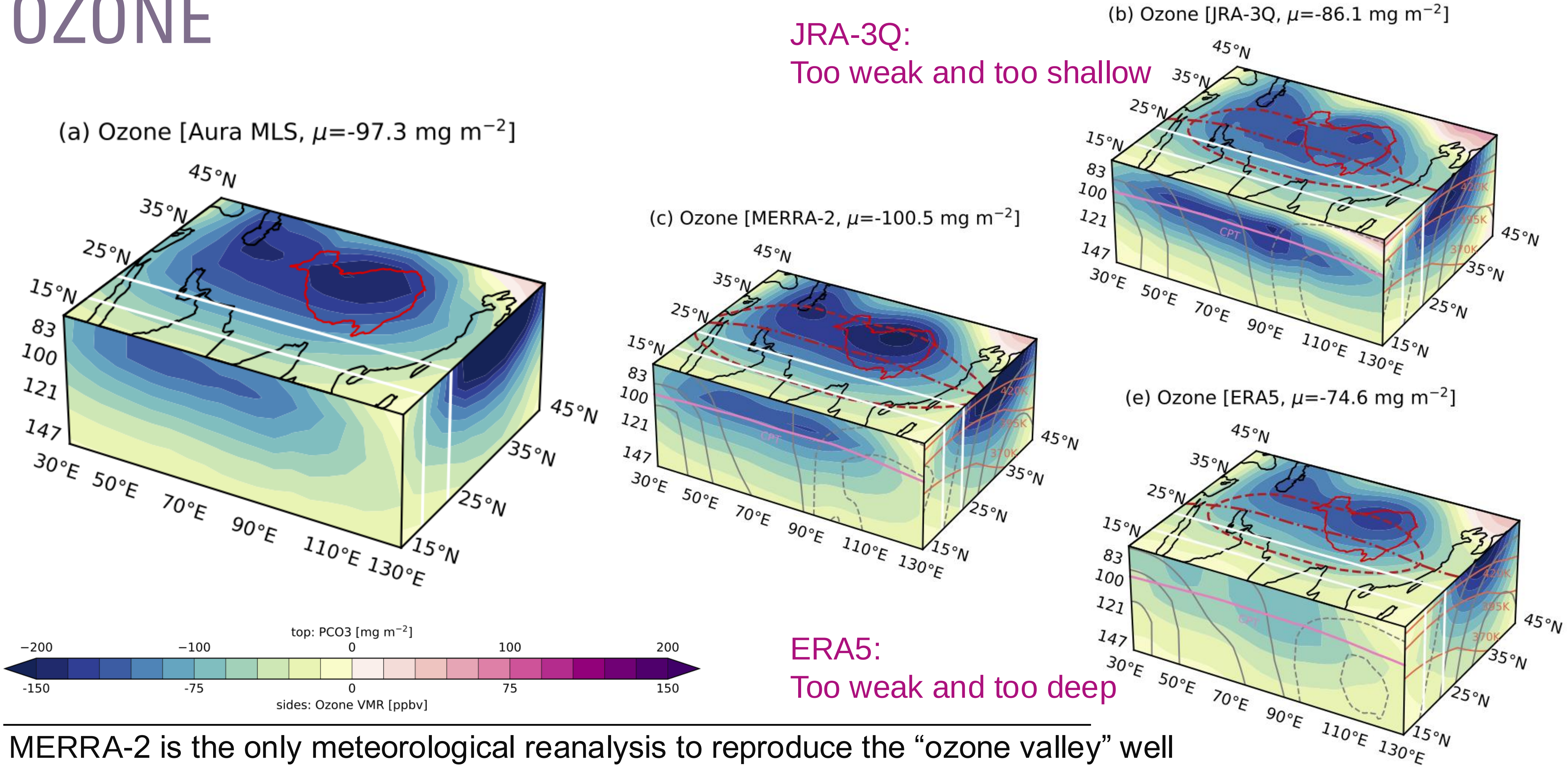


The seasonal “ozone valley”, produced largely by convective dilution and a higher tropopause

CLIMATOLOGY:

OZONE

JRA-3Q:
Too weak and too shallow

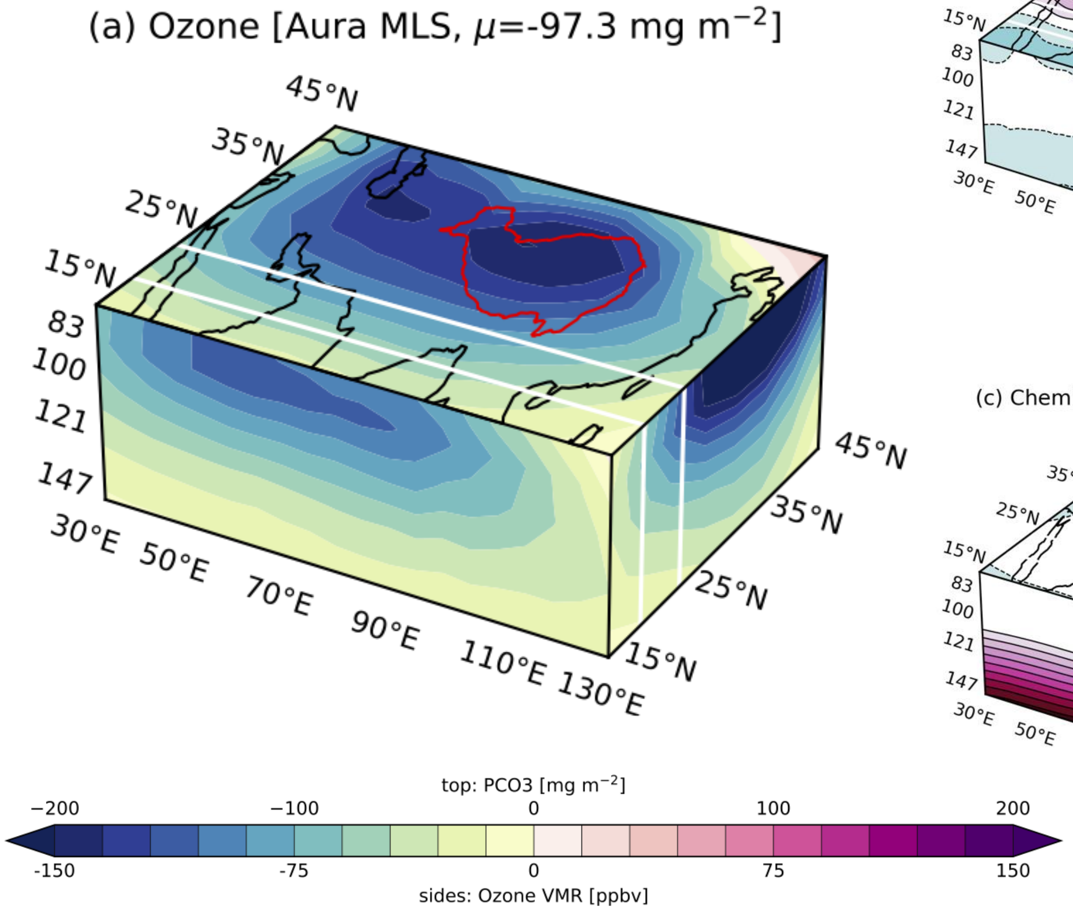


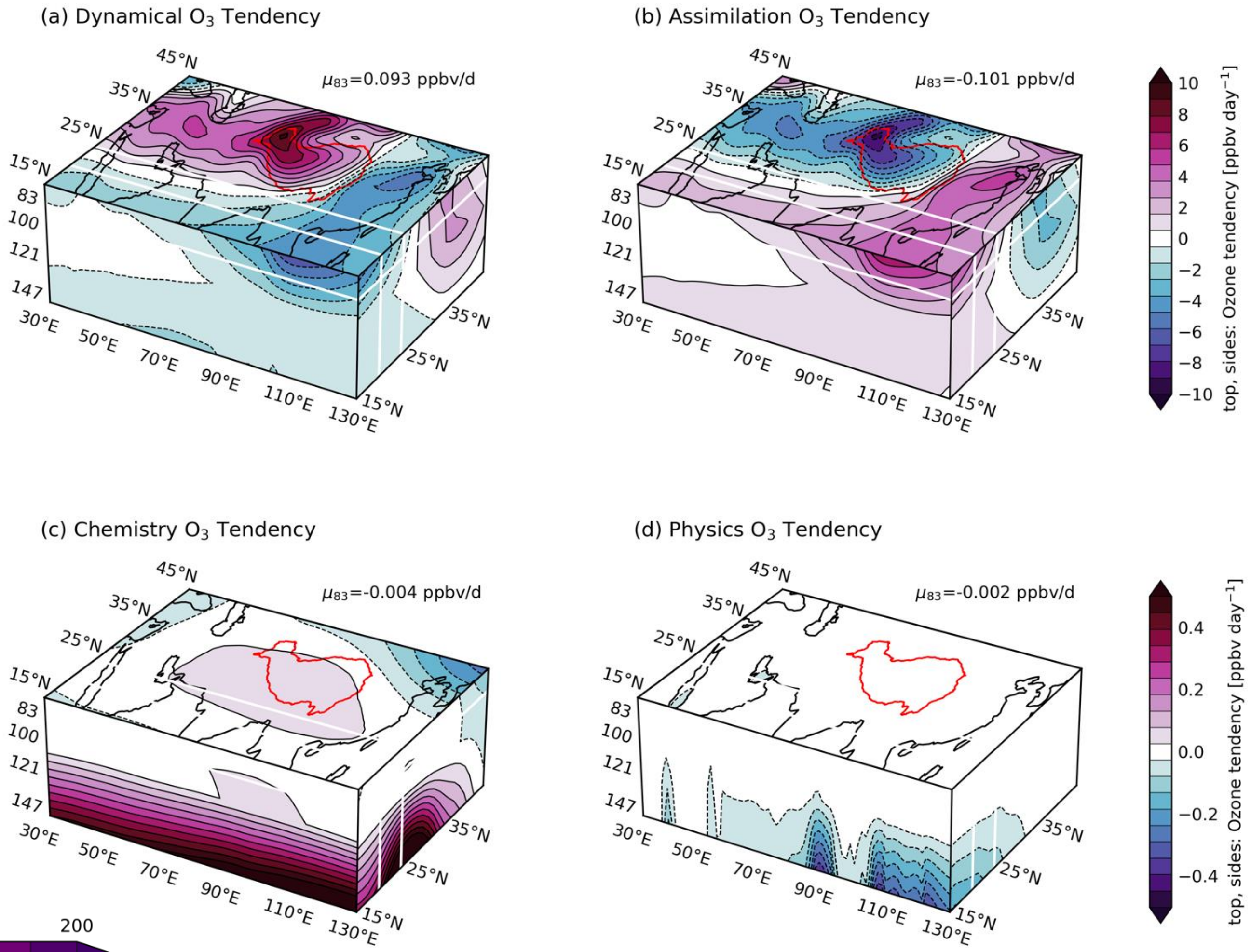
ERA5:
Too weak and too deep

MERRA-2 is the only meteorological reanalysis to reproduce the “ozone valley” well

CLIMATOLOGY:

OZONE





However, MERRA-2 relies heavily on data assimilation to maintain good agreement with MLS

VARIABILITY:

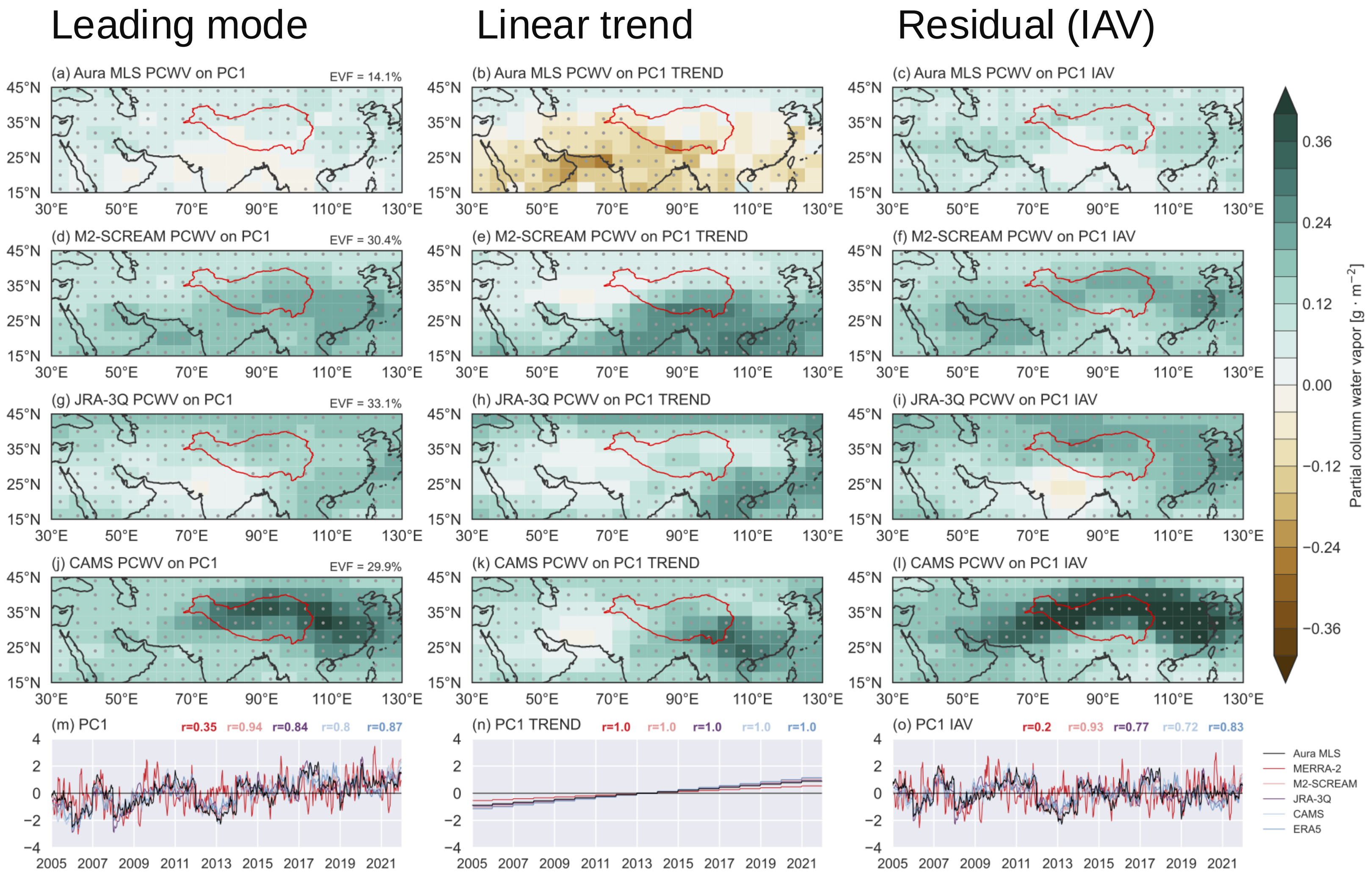
Strong agreement with MLS (except MERRA-2):
Independently calculated detrended PCs: r ~ 0.7 to 0.9

INTERANNUAL

Method: EOF analysis applied to horizontal and vertical variability

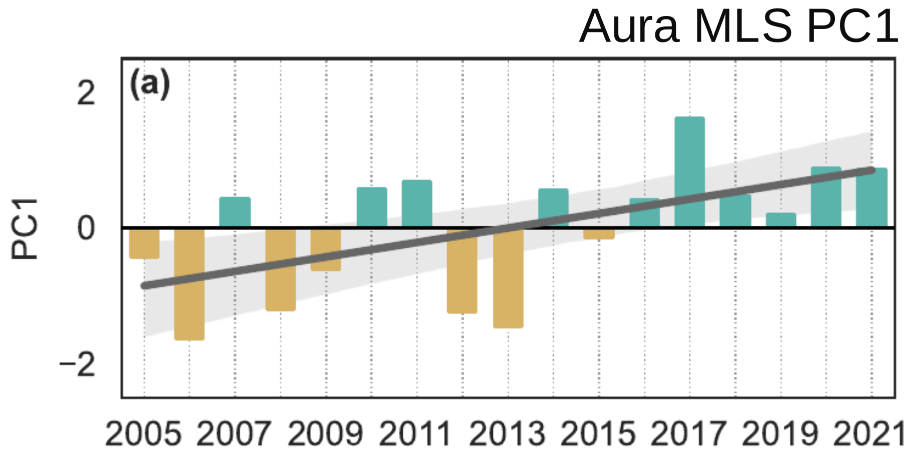
Results:

- Defined by regional-scale moist or dry anomalies
- All reanalyses capture the variations except for MERRA-2
- Although reanalyses agree on the trend, Aura MLS does not

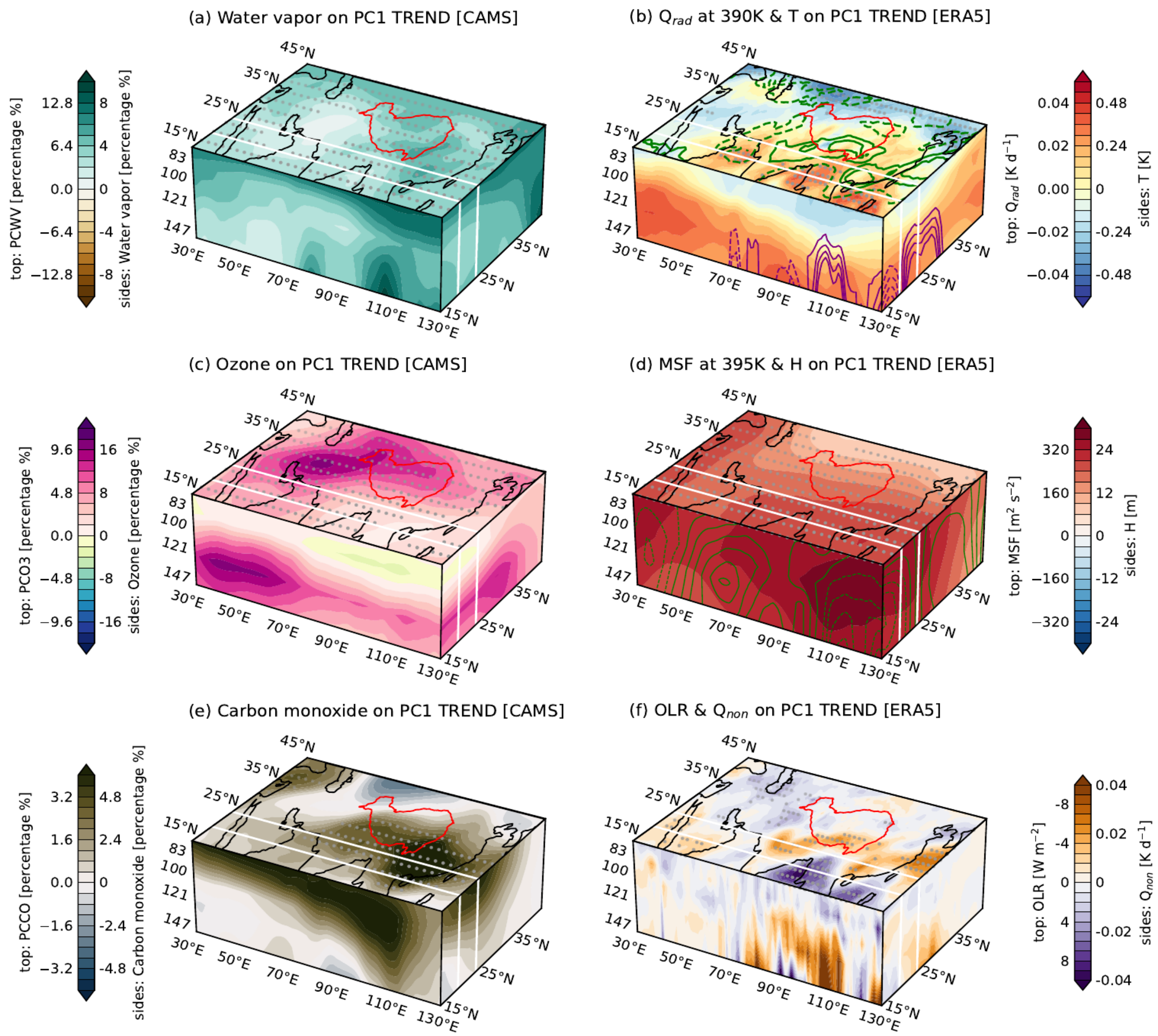


VARIABILITY:

TREND?

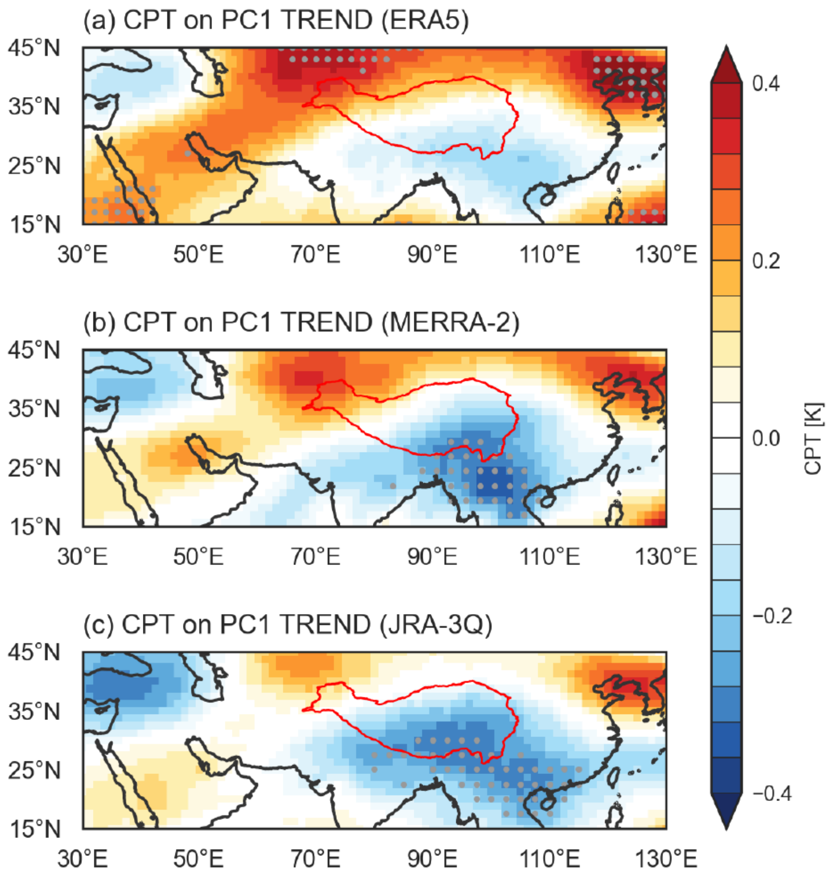


- Largest changes in southeastern quadrant and near 68 hPa
- Signs of tropospheric warming, especially in the SE
- Stronger convection over SE Asia and SE Tibetan Plateau indicated (CO, IWC, HCC, OLR, …)



VARIABILITY:

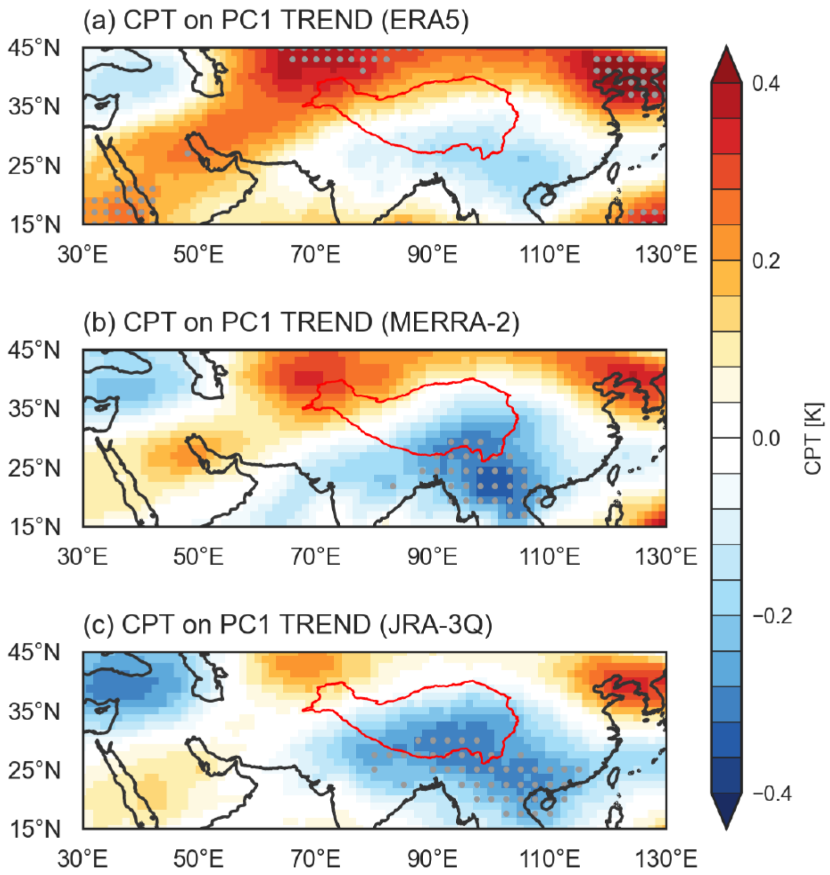
TREND? PROBABLY NOT.

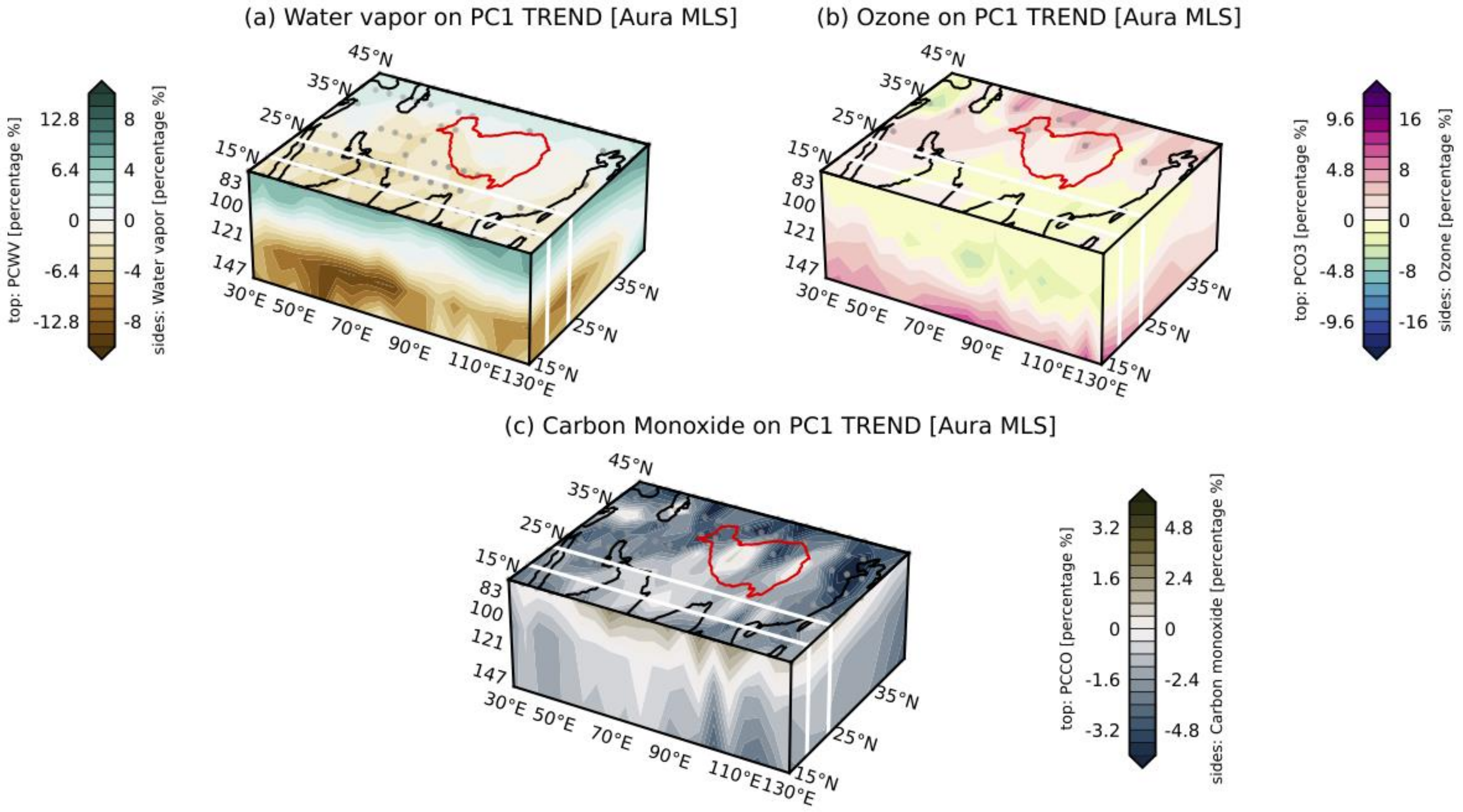


But cold points in the SE got colder...

VARIABILITY:

TREND? PROBABLY NOT.





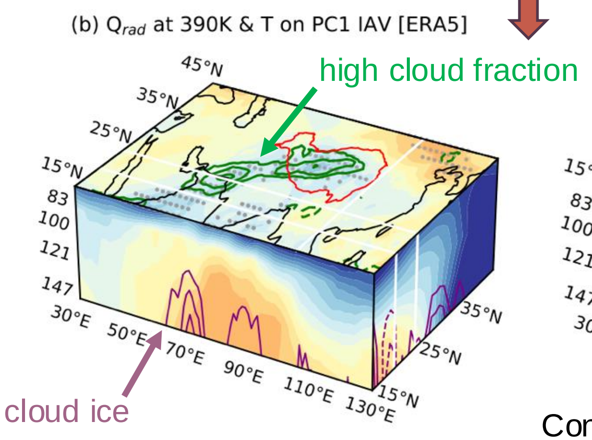
But cold points in the SE got colder... …and composition changes observed by MLS don’t match well

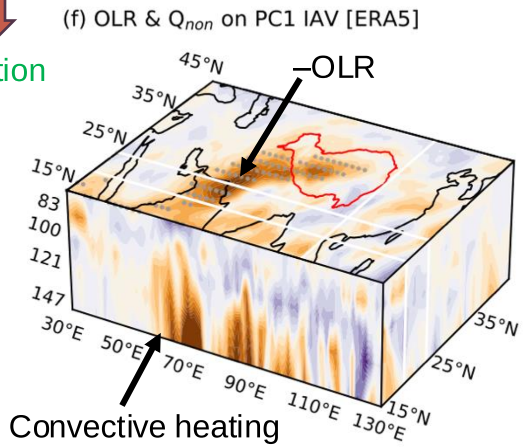
Assessing the trend

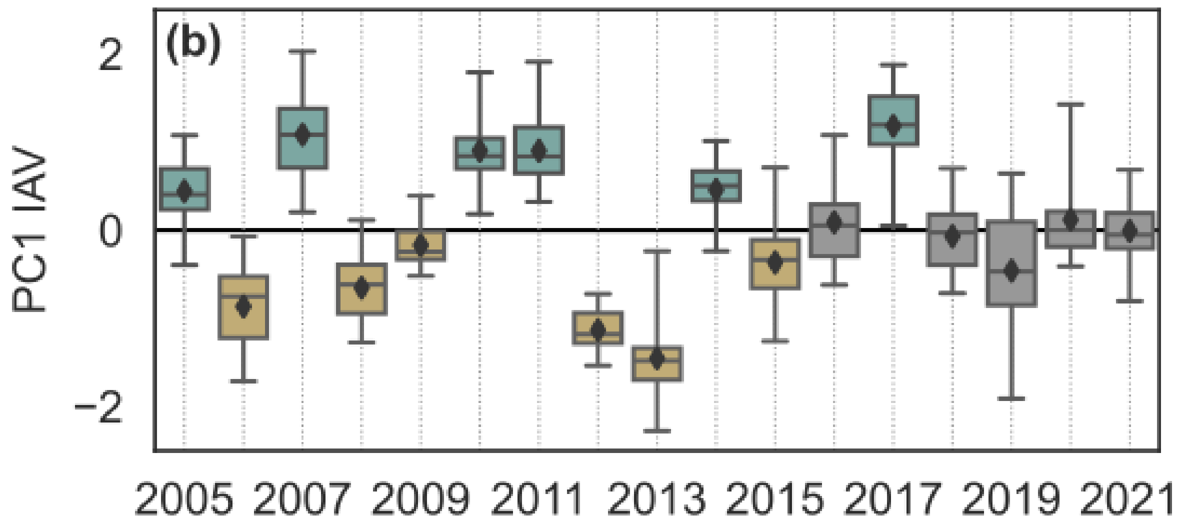
(✓) Consistency across reanalyses
(✗) ~~Consistency with observations~~
(✓) Plausible physical explanation

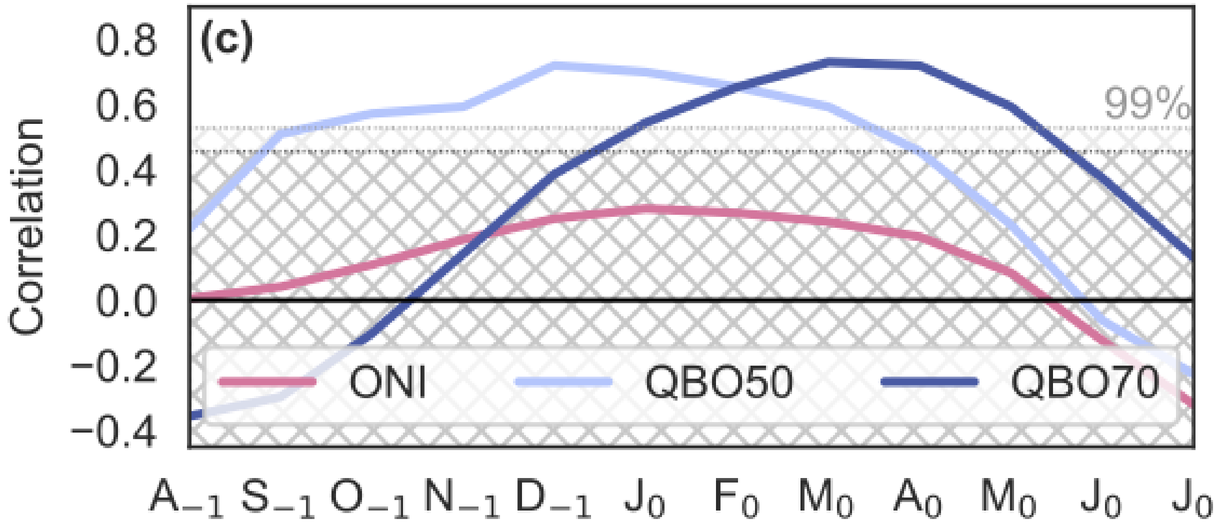
VARIABILITY: INTERANNUAL

- Correlated with QBO, with phase set by T anomalies during pre-monsoon during pre-monsoon
- Remarkably persistent – same sign for all pentads in 7 of 17 years
- Persistence may relate to stronger convection in southwest



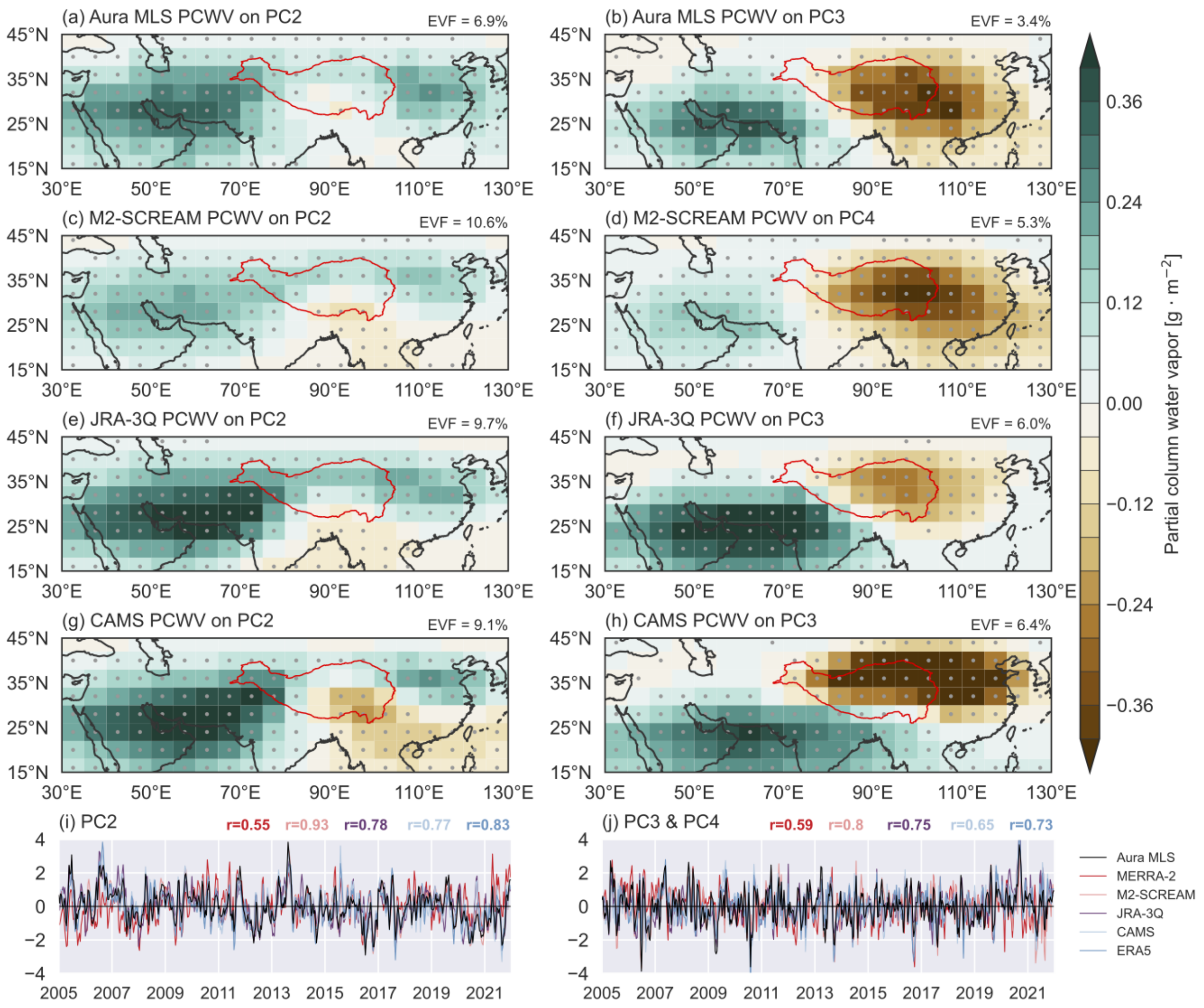






VARIABILITY: SUBSEASONAL

Split vortices + northward shifted anticyclone



Canonical ‘Tibetan Plateau’ – ‘Iranian Plateau’ dipole modes

Independent PCs: r ~ 0.6 to 0.9

Independent PCs: r ~ 0.6 to 0.8

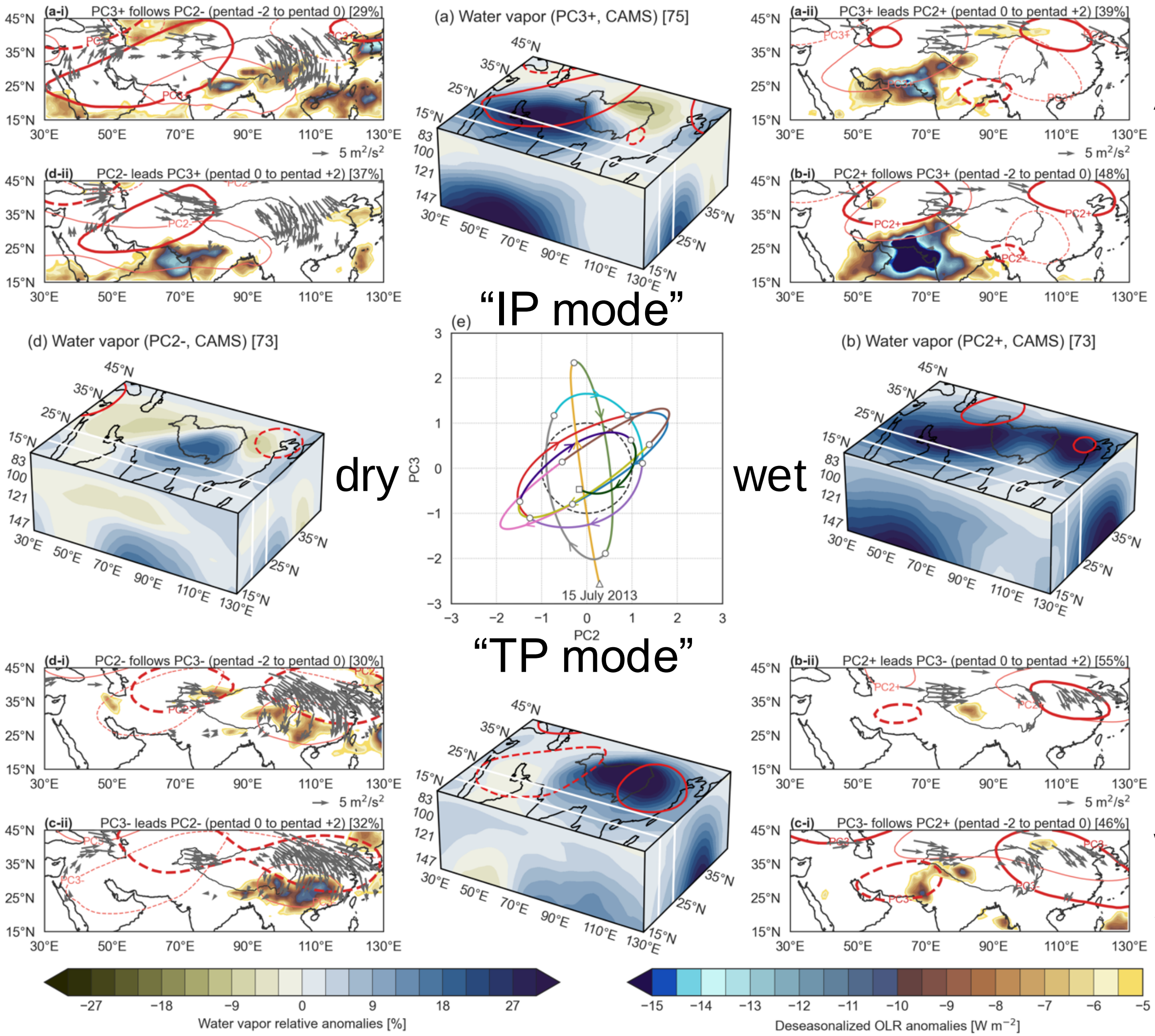
VARIABILITY: SUBSEASONAL

Convective system starts to develop over NE Arabian Sea

~10 days after

Strong convection over Arabian Sea & Indus Valley

~10 days before



~10 days before

Strong wave breaking and heavy rain over South China

~10 days after

Wave propagates along subtropical jet waveguide

Quasi-biweekly waves, active/break, and other organized intraseasonal variability

RECAP

- All reanalyses have hemispheric moist biases, but regional anomalies are captured well
- The main balance is between advective moistening and condensation drying, but data assimilation is comparable to the sum of these
- Reanalyses produce a robust increasing trend in UTLS WV over 2005-2021, but this trend is neither observed by Aura MLS nor consistent with changes in cold point temperature
- Interannual variability is dominated by QBO-related temperature anomalies during the pre-monsoon and is captured well by reanalyses, except for MERRA-2
- Subseasonal variability arising from east-west shifts of convective activity is reproduced well by all reanalyses and can be partially attributed to convectively coupled waves
- Although reanalyses broadly capture the “ozone valley”, ERA5 and JRA-3Q show large biases and MERRA-2 relies heavily on data assimilation

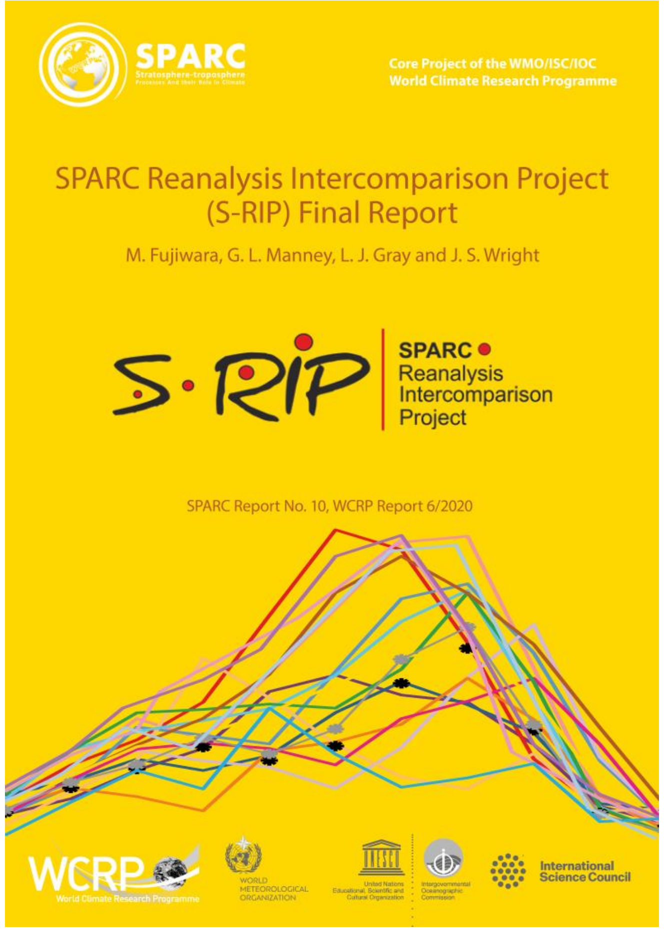
Comments, questions, suggestions to: jswright@tsinghua.edu.cn

OUTLOOK

- The end-of-life for Aura MLS will leave significant observational gaps in this region, which is characterized by significant variability at a wide range of scales
- Development of retrieval-based assimilation tools for UTLS water vapor like that used for Aura MLS in M2-SCREAM has some potential to help fill this gap (e.g. SAGE III)
- The ECMWF reanalyses, which do not assimilate MLS and prohibit increments above the tropopause, may also remain a useful source of information in this region
- JRA-3Q water vapour at 100 hPa and above is better than JRA-55 but remains problematic
- Prohibiting increments above the tropopause would make reanalysis stratospheric water vapor products much more useful
- Inclusion of CO or CO-like tracers would be very valuable even without assimilation

Comments, questions, suggestions to: jswright@tsinghua.edu.cn

REANALYSIS INTERCOMPARISON PROJECT



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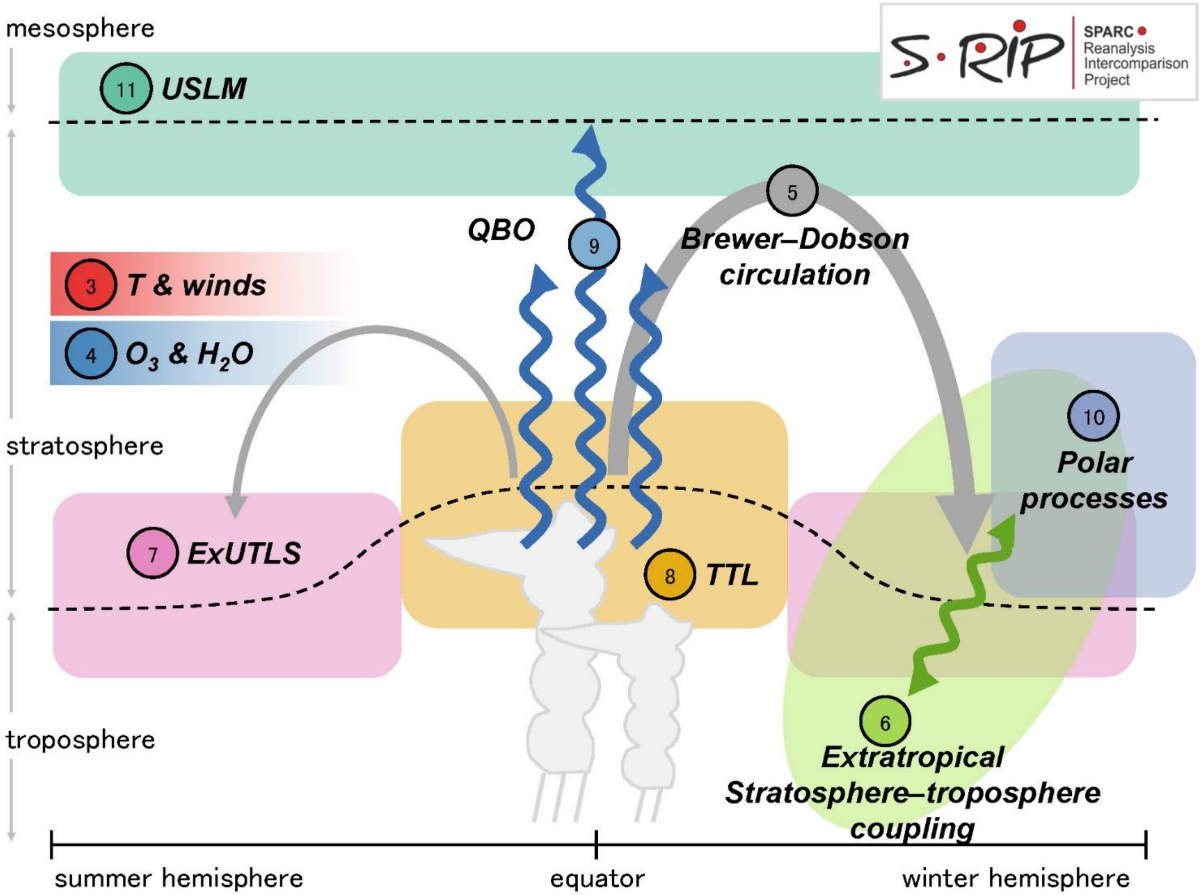

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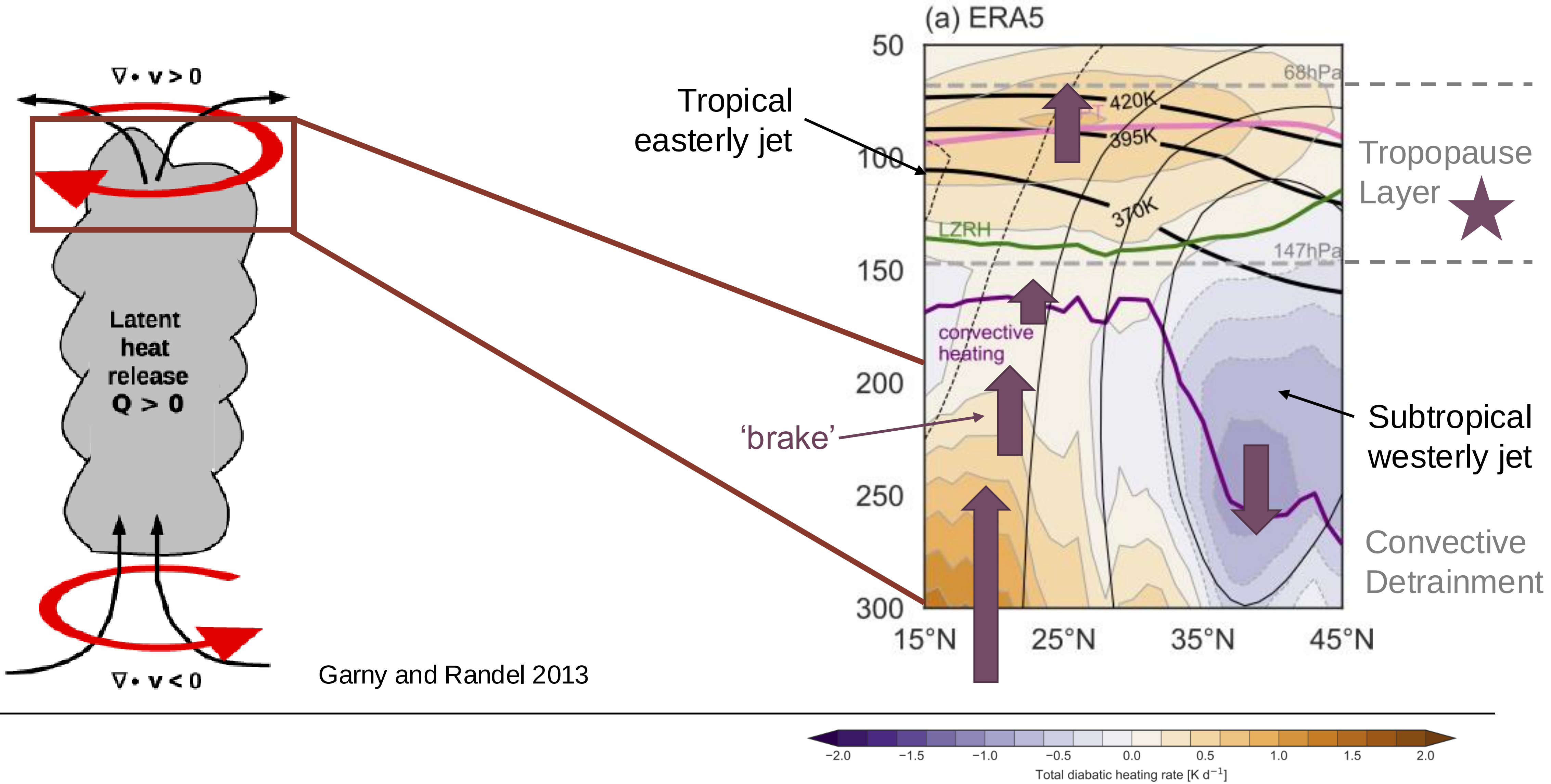
ASIAN MONSOON ANTICYCLONE: CIRCULATION

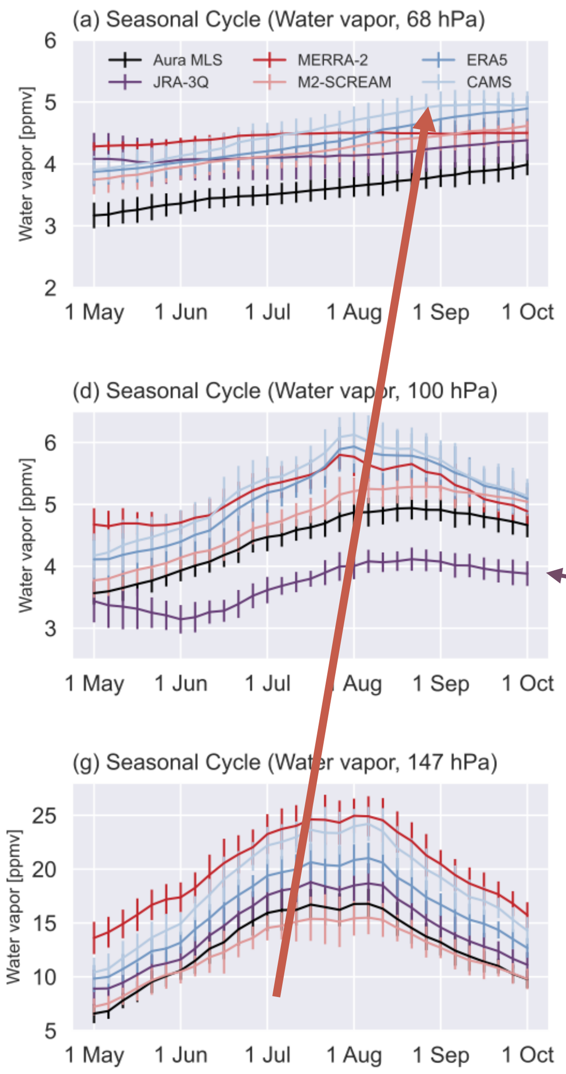


Garny and Randel 2013

CLIMATOLOGY:

WATER VAPOR

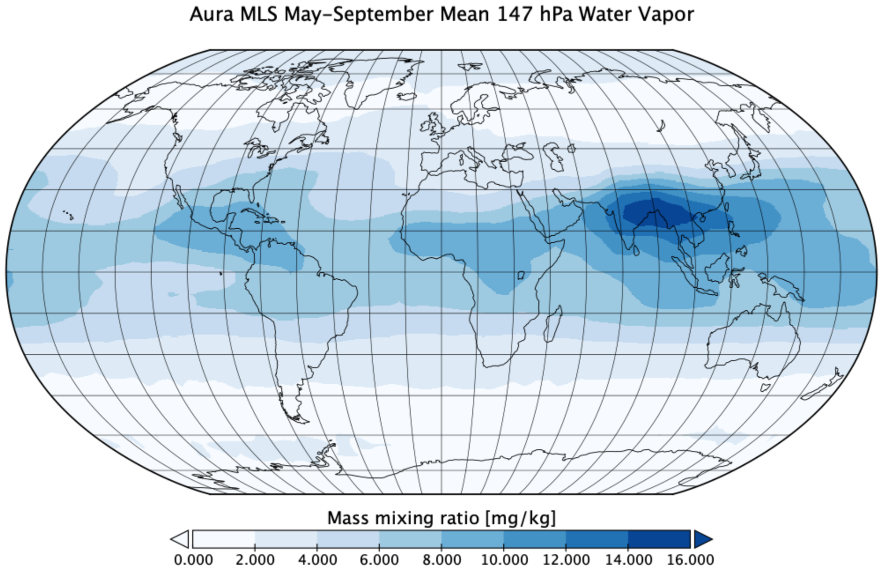
Reanalyses capture the upward spiraling 'tape recorder' reasonably well in the tropopause layer, though with somewhat different transit times.

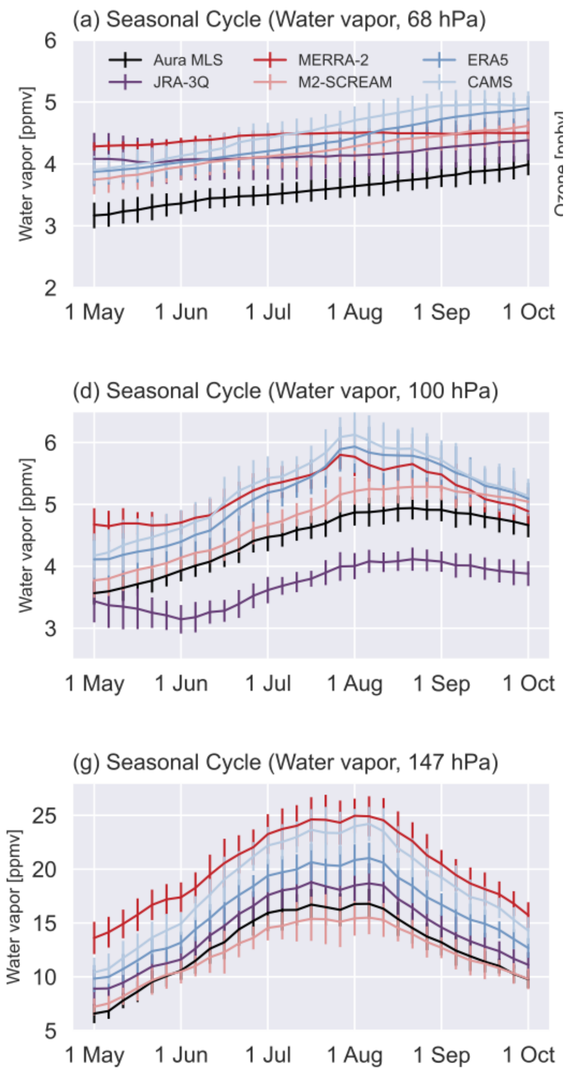


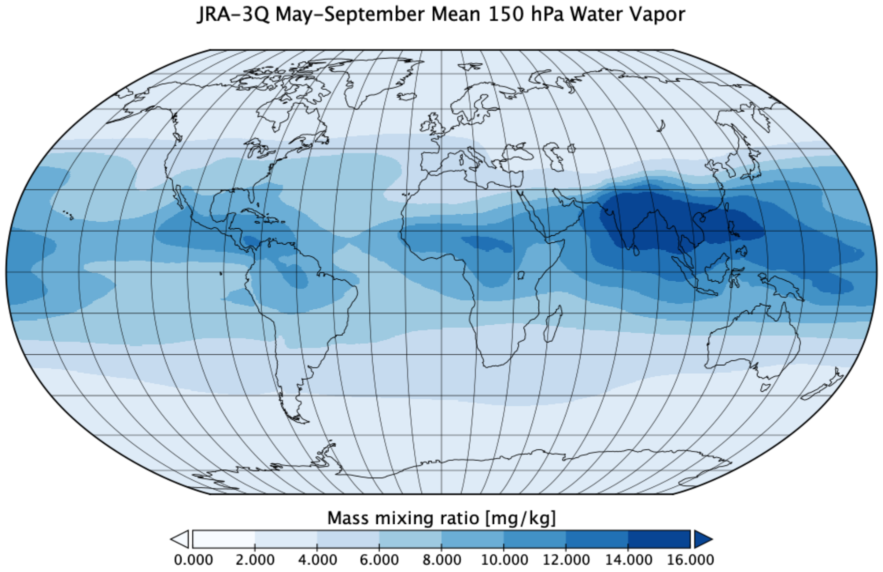
Biases at each level are fairly consistent through the seasonal cycle

This looks like an error.
It is not an error.

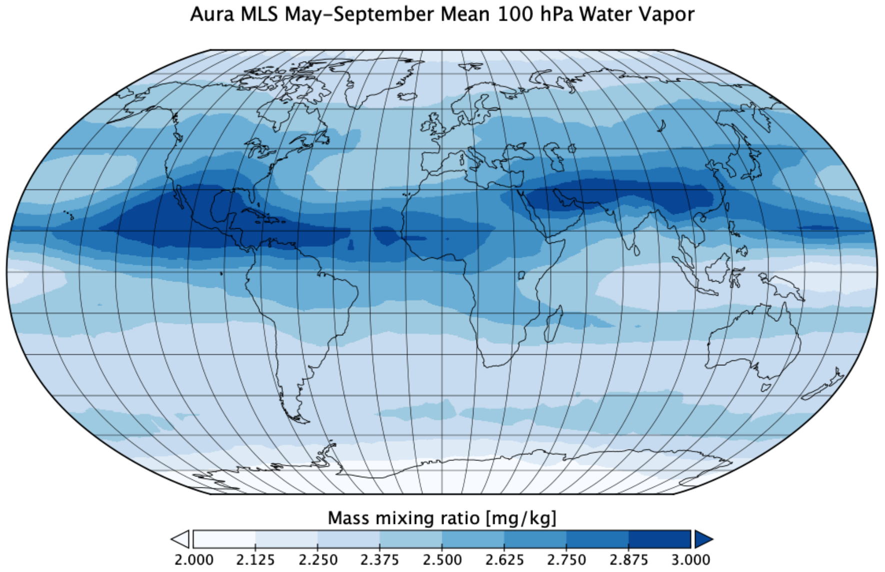
CLIMATOLOGY:
WATER VAPOR

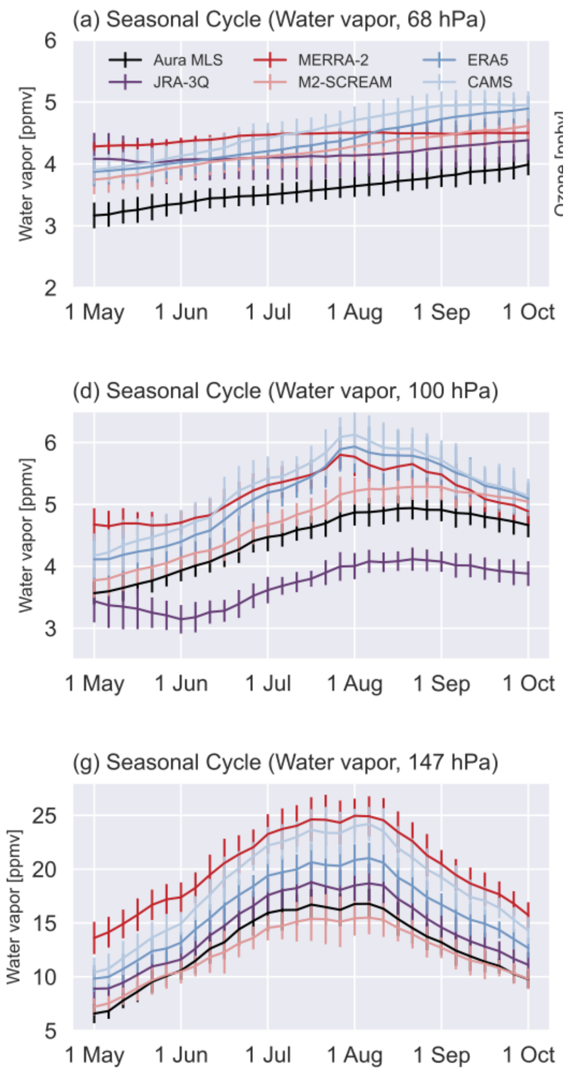


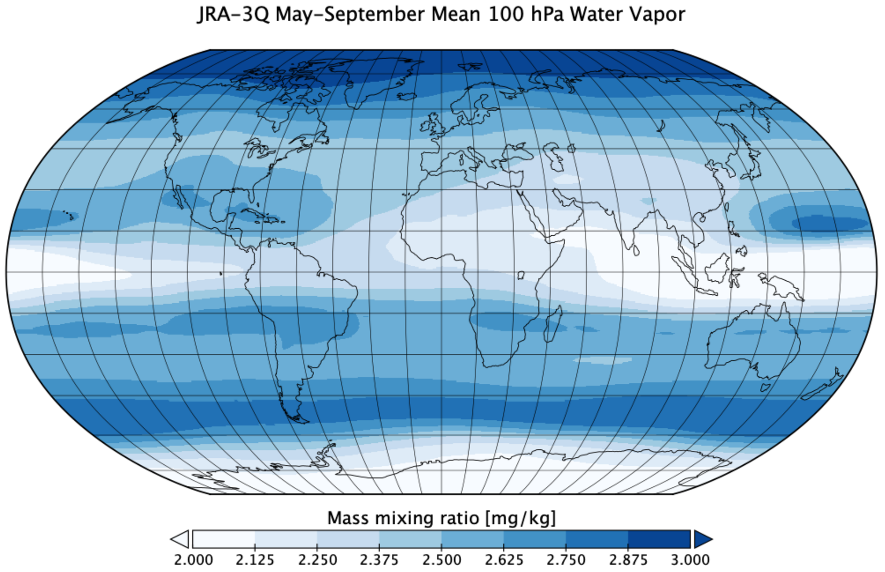




CLIMATOLOGY:
WATER VAPOR





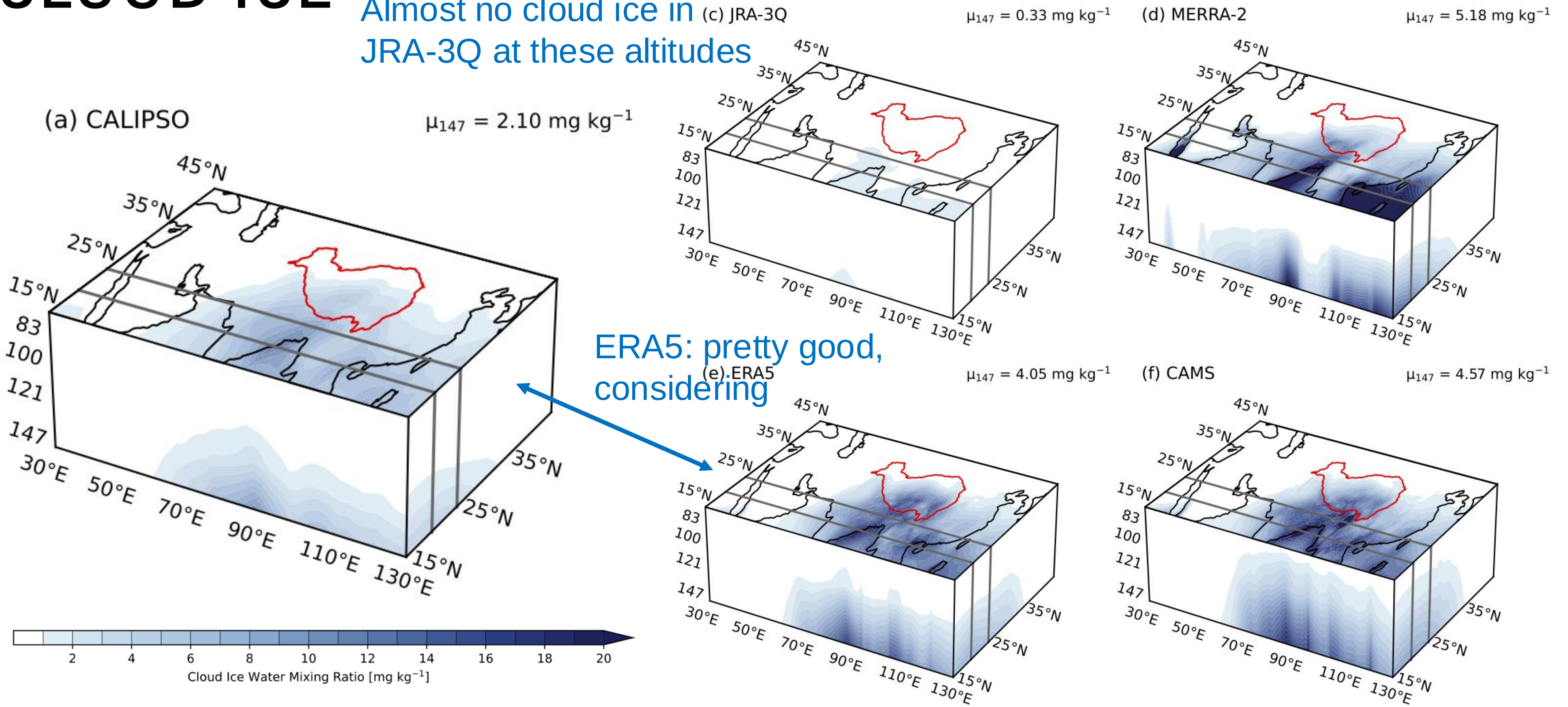


CLIMATOLOGY: CLOUD ICE

MERRA-2: too much ice over South China Sea

Almost no cloud ice in JRA-3Q at these altitudes

ERA5: pretty good, considering



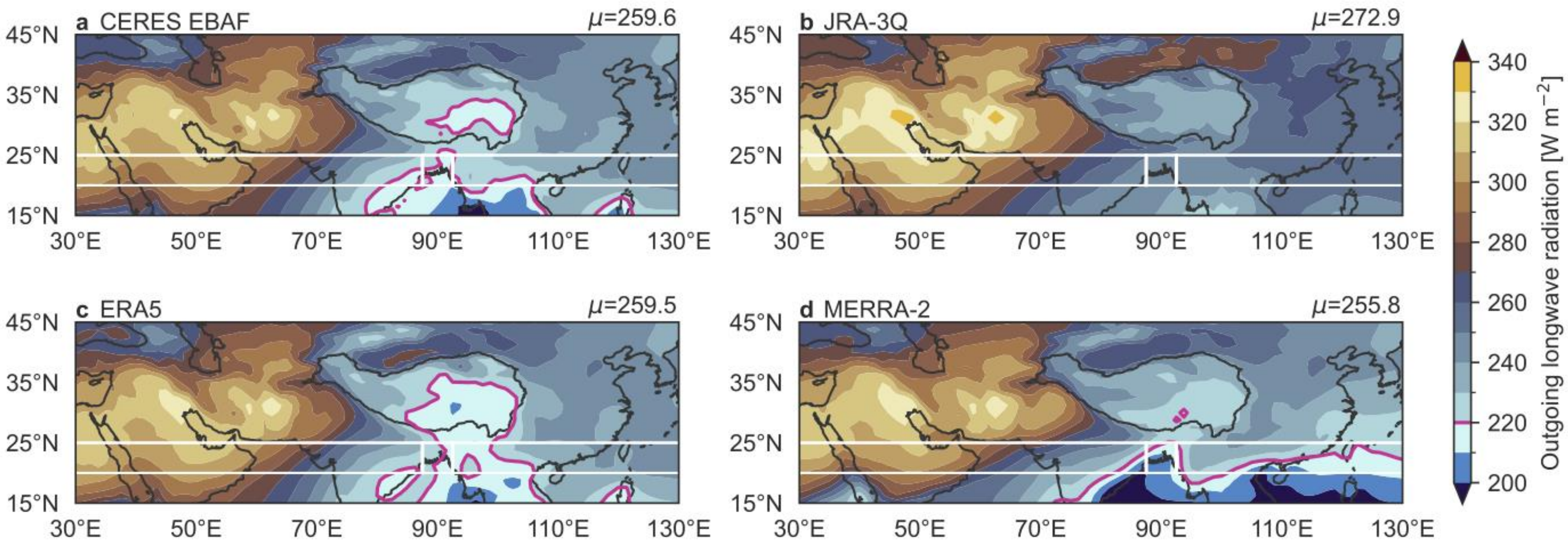
CAMS: much deeper than others

Observationally-based data: CALIPSO L3-ICE

CLIMATOLOGY:

CLOUD RADIATIVE EFFECTS

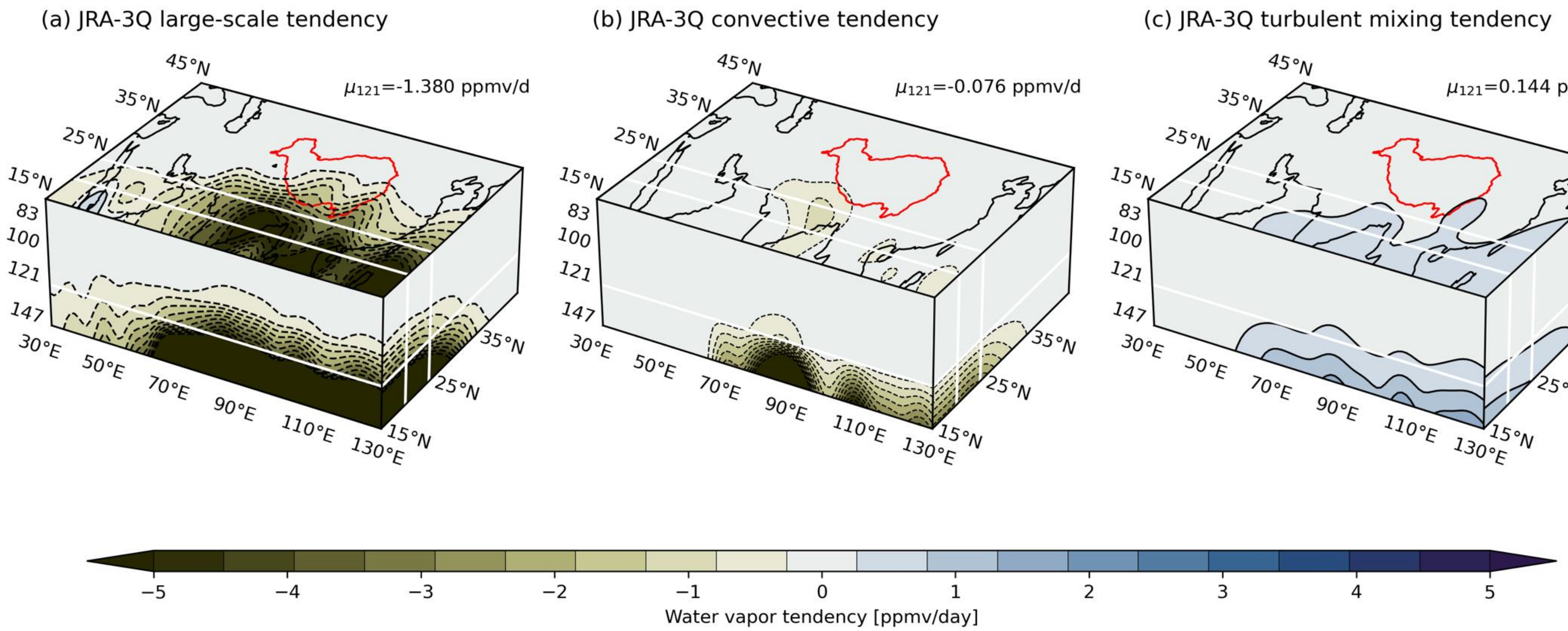
Discrepancies in mean OLR are consistent with those in cloud ice: JRA-3Q OLR is too large, MERRA-2 OLR is too small over tropical oceans, and ERA5 agrees well with CERES



Observationally-based data: CERES EBAF

CLIMATOLOGY:

BUDGETS

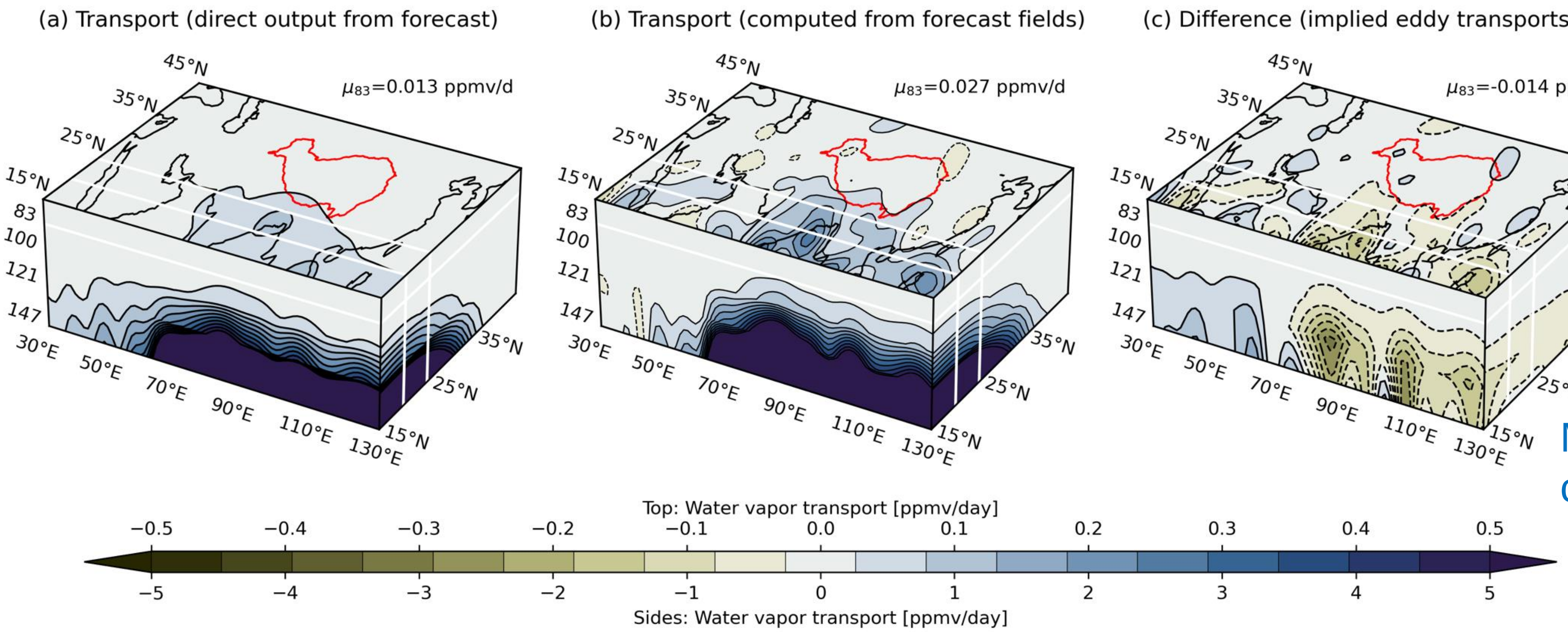


Convective influences reach into the tropopause layer

CLIMATOLOGY:

BUDGETS

Explicitly accounting for assimilation reveals another term:



Missing advective component

Due to the reanalysis model and our calculations having different grids and time steps