

Insights of tropical cyclones responses to global warming from GNSS RO data over the past 16 years

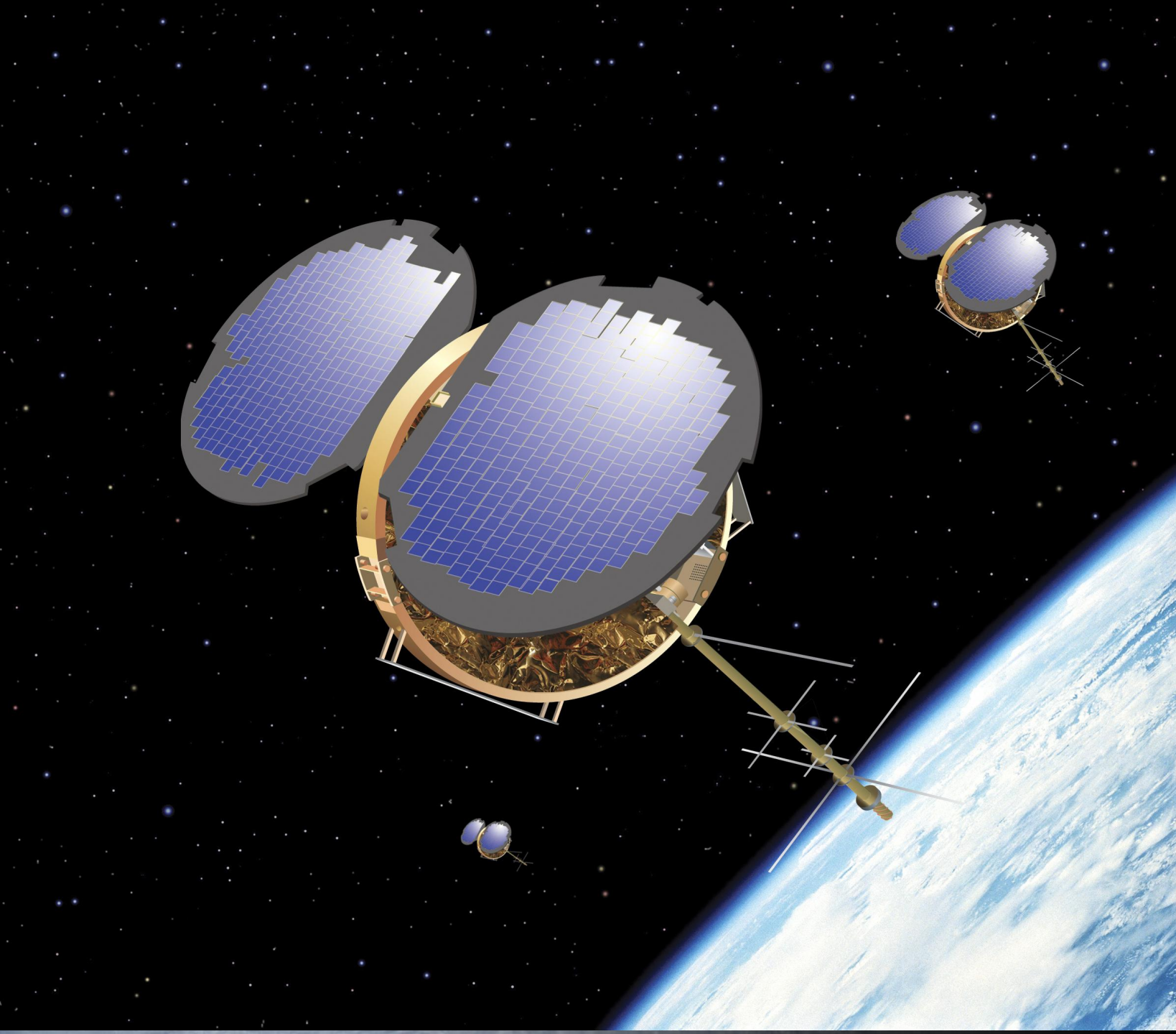
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COSMIC/JCSDA Workshop & IROWG-10 in Boulder, Colorado



Content

Background

Data and Methodology

Results & Discussions

Conclusions

Climate changes

Carbon Dioxide

↑ **420** parts per million

+

Global Temperature

↑ **1.1** °C since preindustrial

+

Methane

↑ **1923.6** parts per billion

+

Arctic Sea Ice Minimum Extent

↓ **12.3** percent per decade since 1979

+

Ice Sheets

↓ **424** billion metric tons per year

+

Sea Level

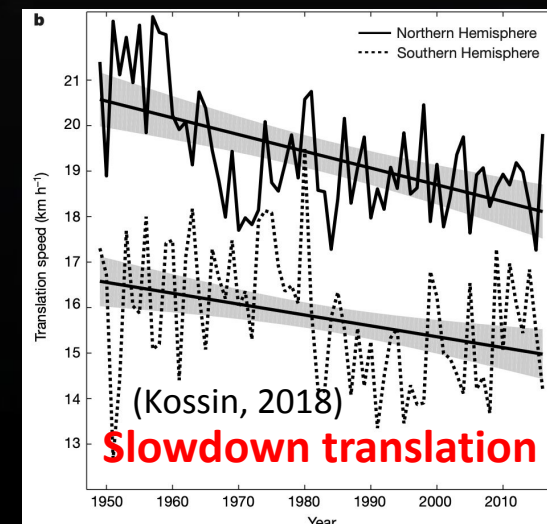
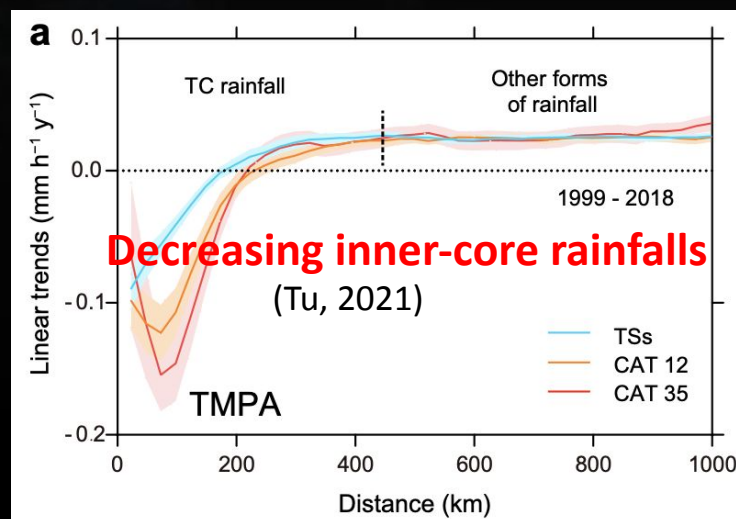
↑ **4** inches since January 1993

+

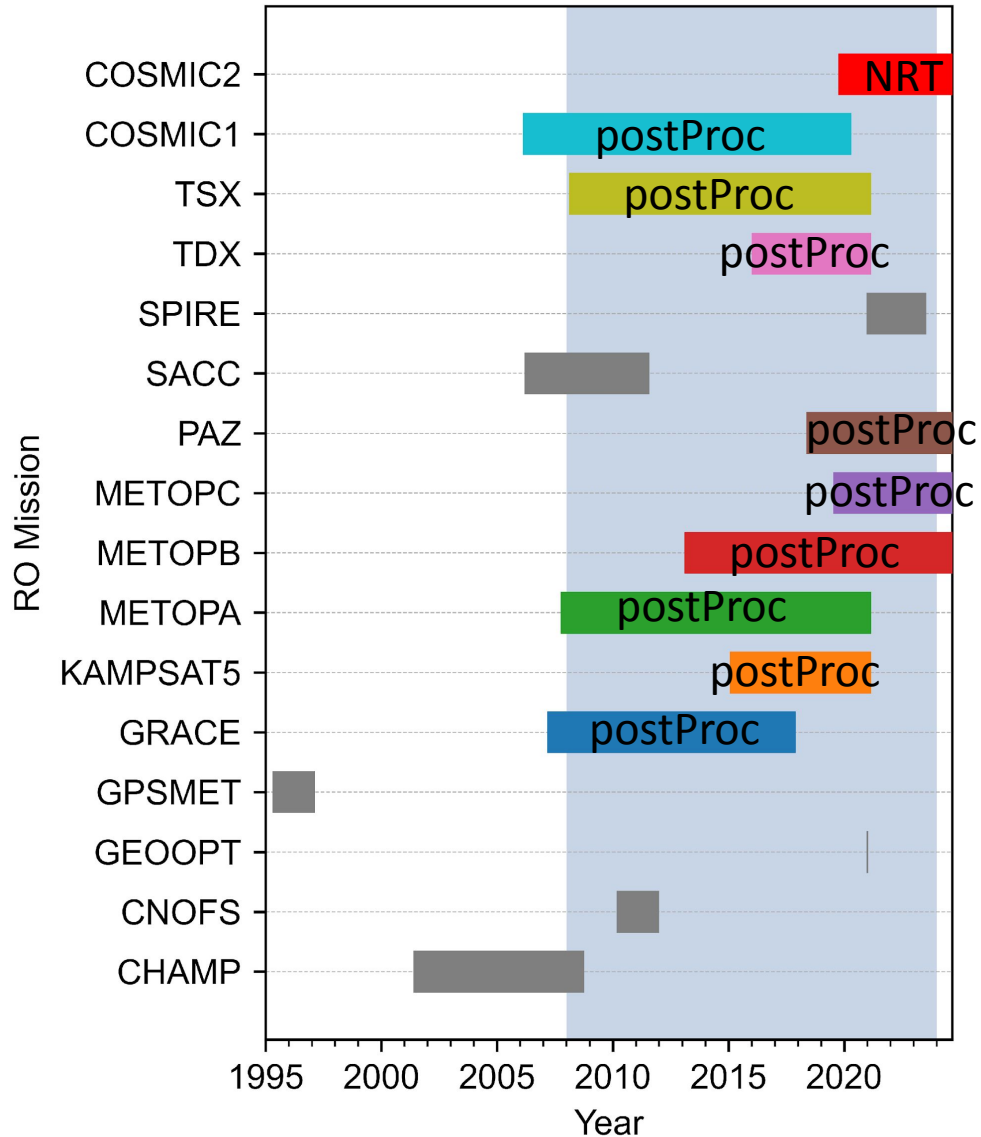
Ocean Warming

↑ **345** zettajoules since 1955

+



GNSS RO data



Water vapor accuracy compared with ground GNSS station and Radiosonde with 1-hour and 150 km matching rule

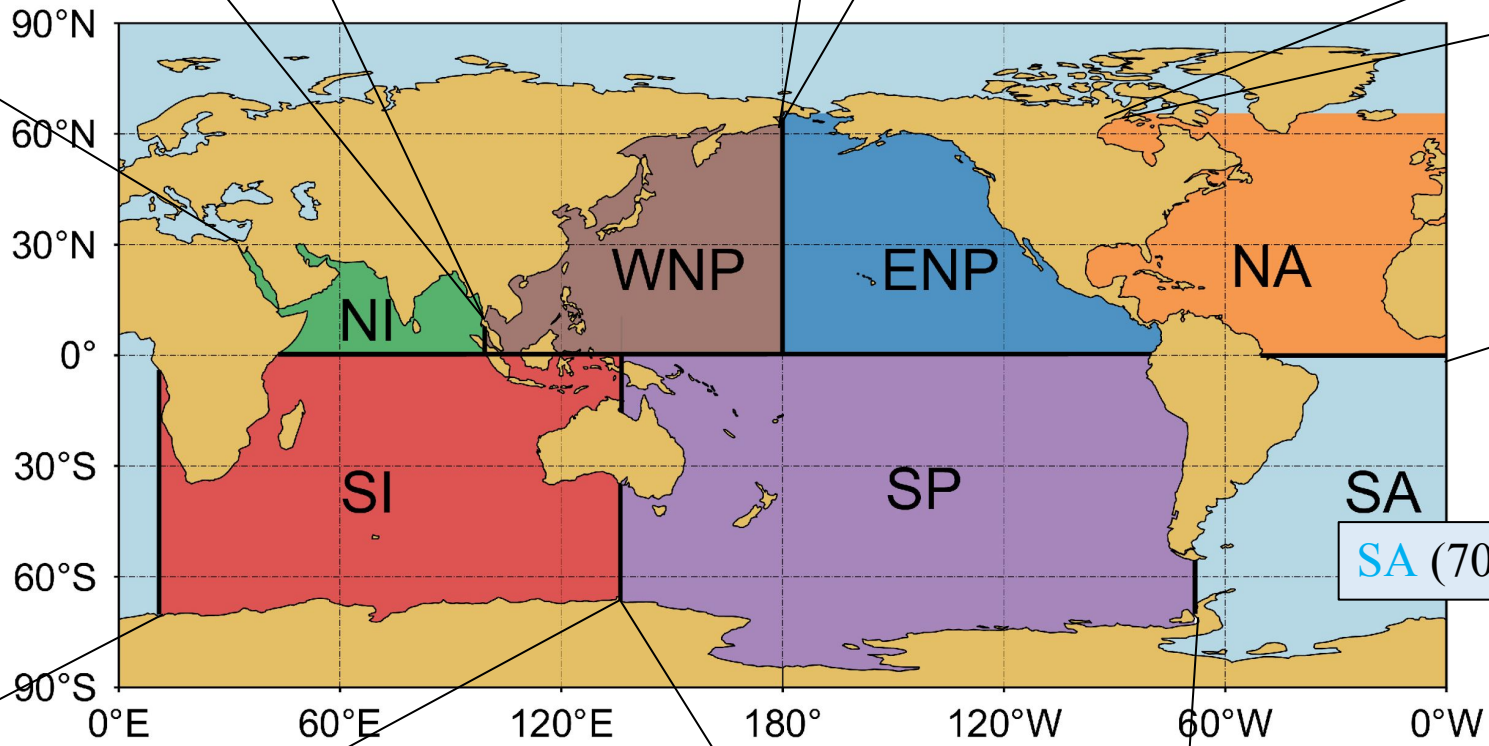
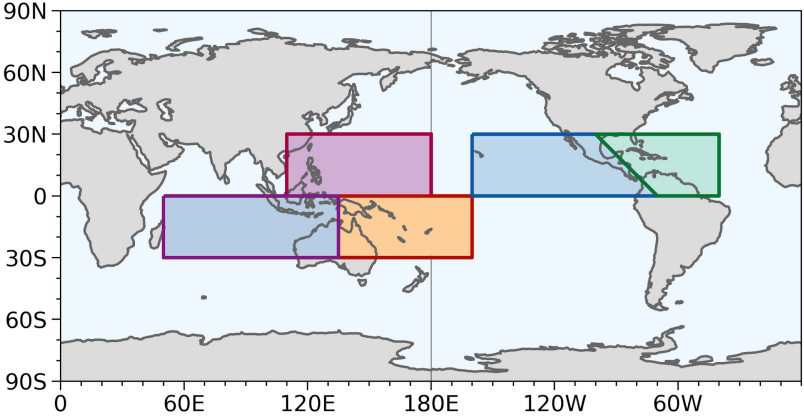
Satellite Mission	GNSS		Radiosonde	
	# of points	RMSE (mm)	# of points	RMSE (mm)
COSMIC1	20097	3.0	5267	2.7
COSMIC2	25388	3.7	5209	3.7
TSX	13075	2.9	4764	2.7
TDX	5469	3.1	1804	2.8
PAZ	3265	2.9	1075	2.6
METOPC	2778	2.9	663	2.6
METOPB	18434	3.0	4782	2.9
METOPA	18206	3.0	4536	2.9
KOMPAST5	14658	2.9	5173	2.6
GRACE	4353	2.5	1459	2.2

Tropical cyclone ocean basins

NI (30° E ~100° E)

WNP (100° E ~180° E)

ENP (western boundary is 180° E, eastern boundary is the coastline of the North America on the North Atlantic)



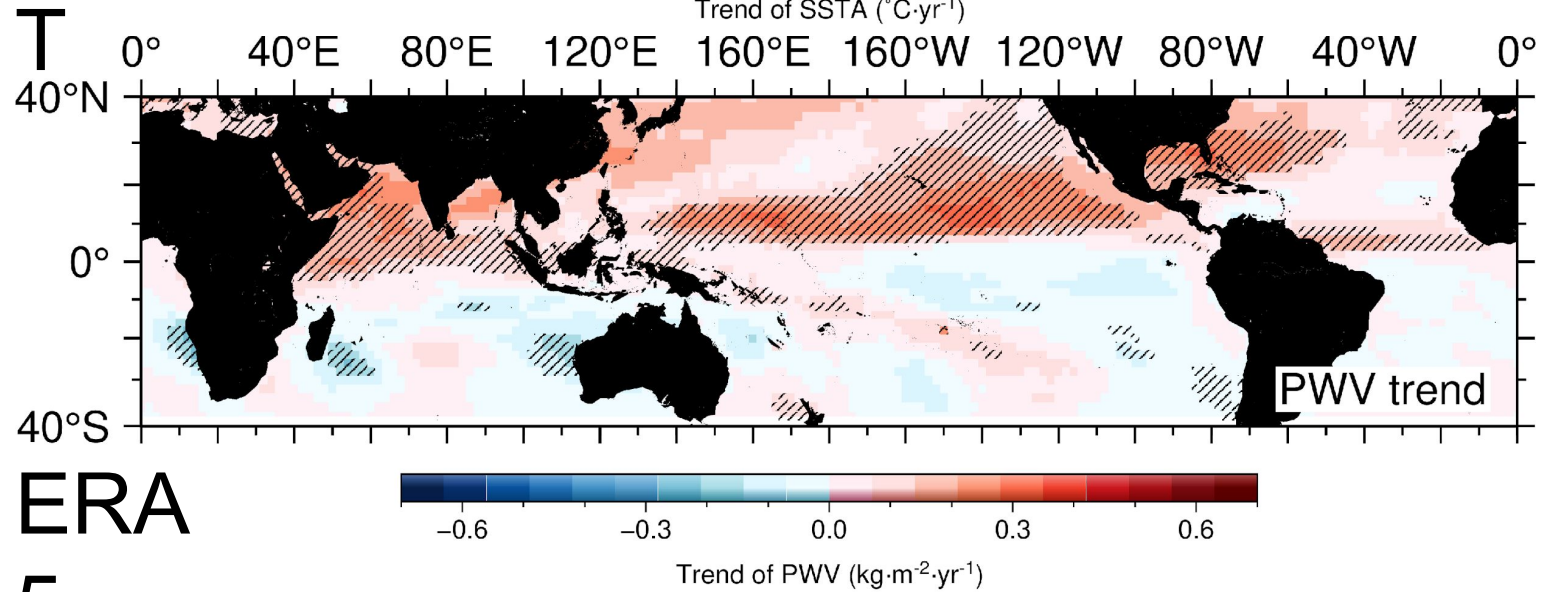
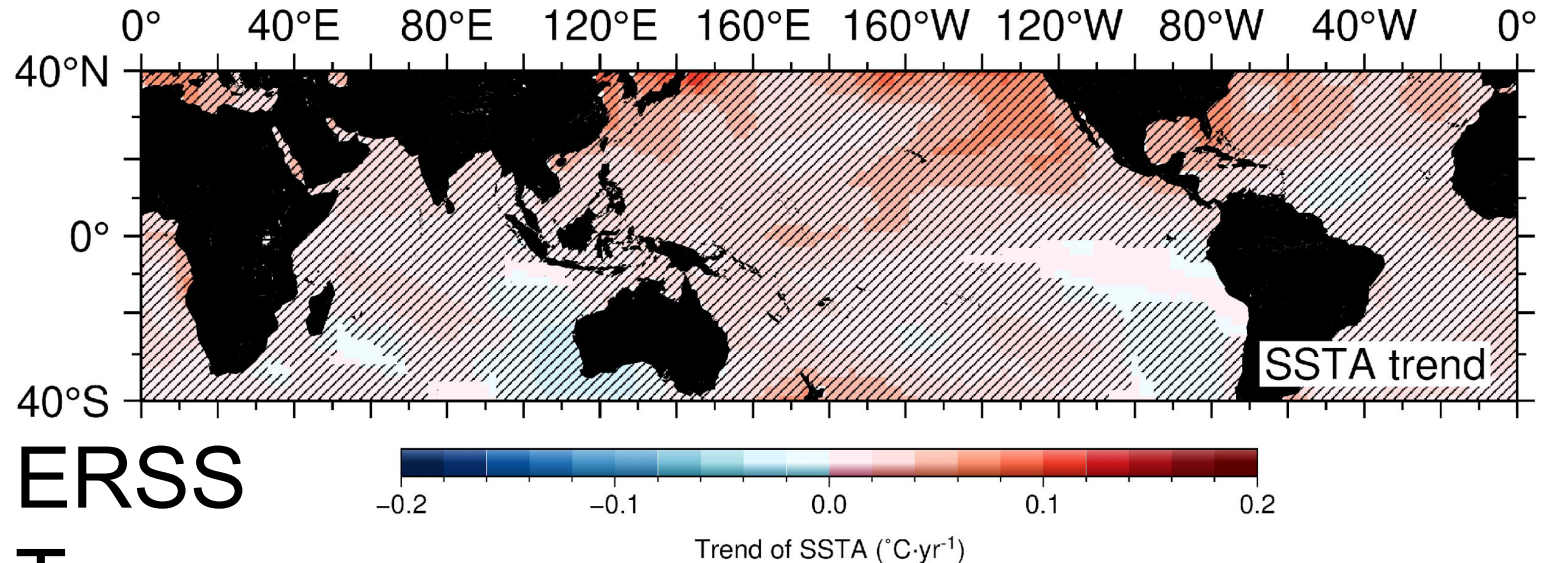
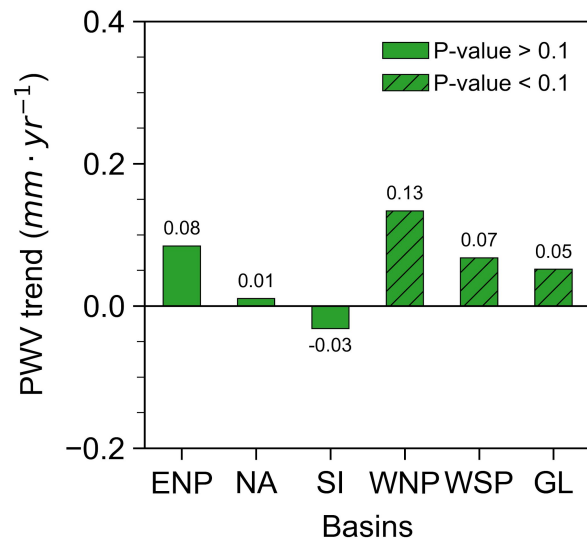
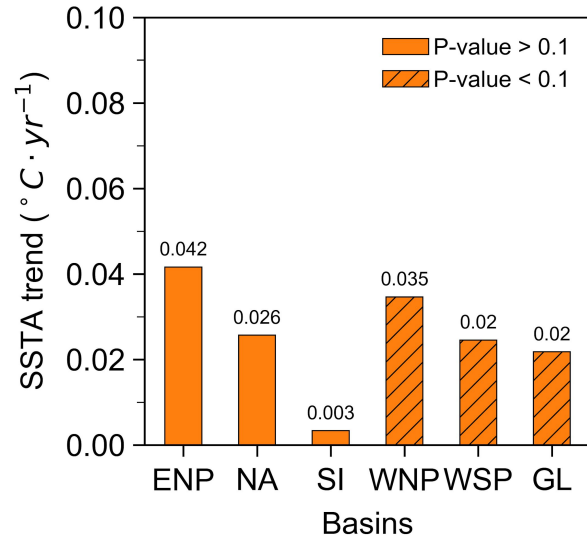
NA (western boundary is the coastline of the North America on the Eastern Pacific, the eastern boundary is 30° E)

SI (10° E ~135° E)

SP (135° E ~70° W)

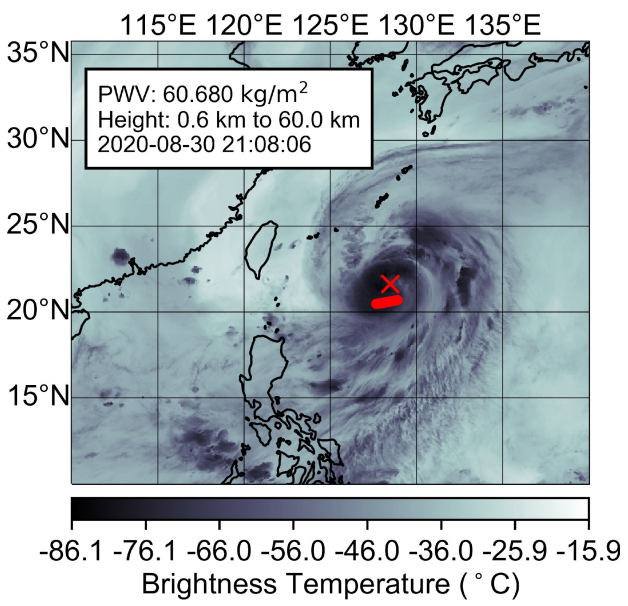
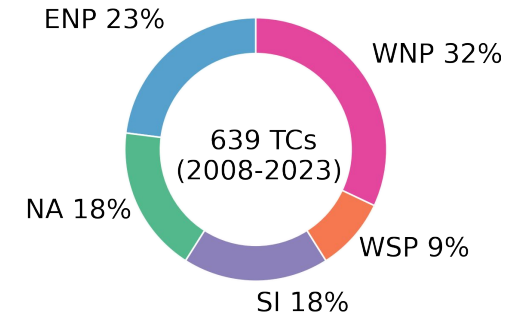
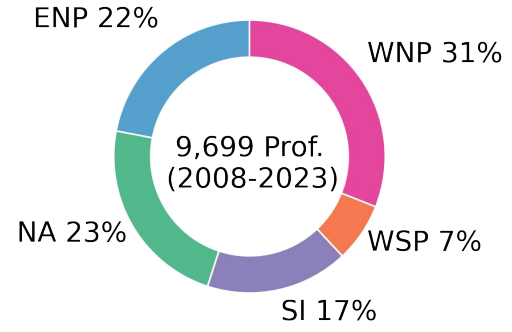
SA (70° W ~10° E)

Short-term trends in SSTA & PWV (2008-2023)

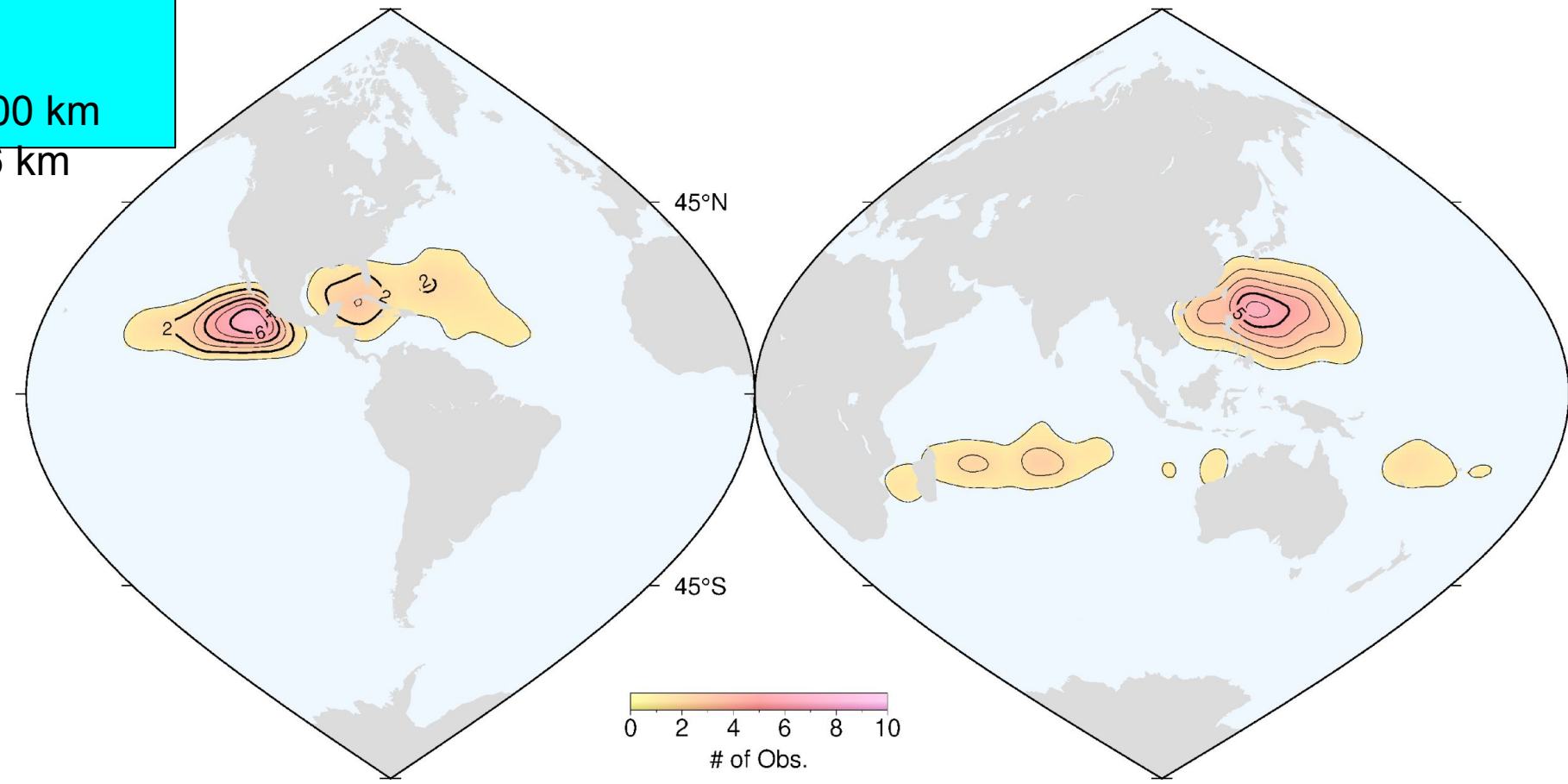


RO observations

- QC:
1. TC intensity with USA_SSHS Cat. 1-5
 2. TC in developing stage with $\delta USA_WIND/\delta t > 0$
 3. Distance from TC center < 600 km
 4. Penetrate depth reaching 1.6 km

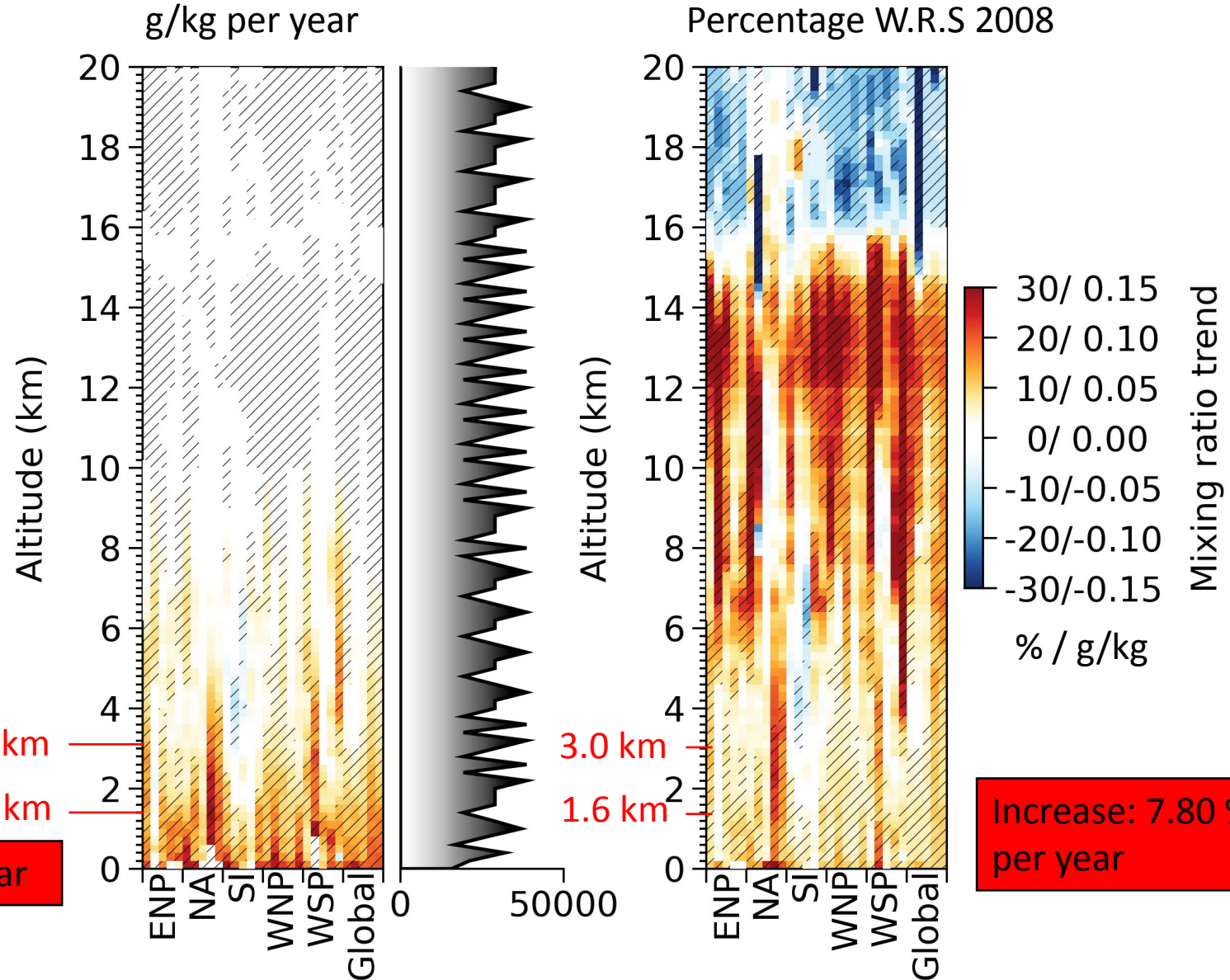


RO-TC pair



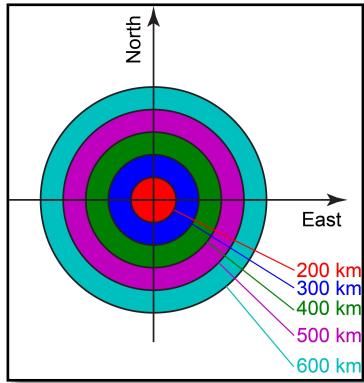
Mixing ratio trend in different altitudes

Mixing ratio trend in g/kg per yr (left) and percentage (right) over the ENP, NA, SI, WNP, WSP, and Global scales. The cross shadow denotes the trend is statistically significant above the 90% confidence level according to a Wald's t test on the linear regression result.

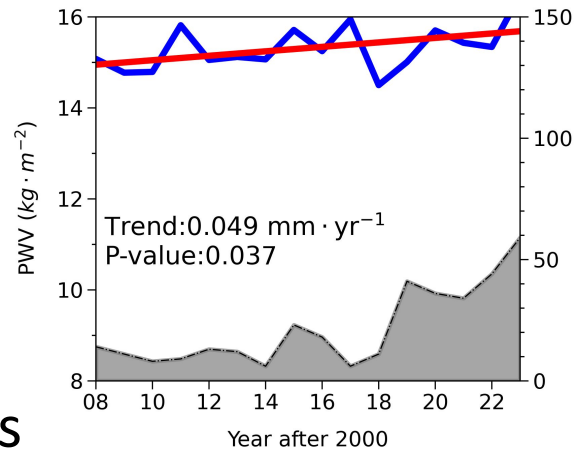


TC water vapor trend @ 1.6-3.0 km (different bands & basins)

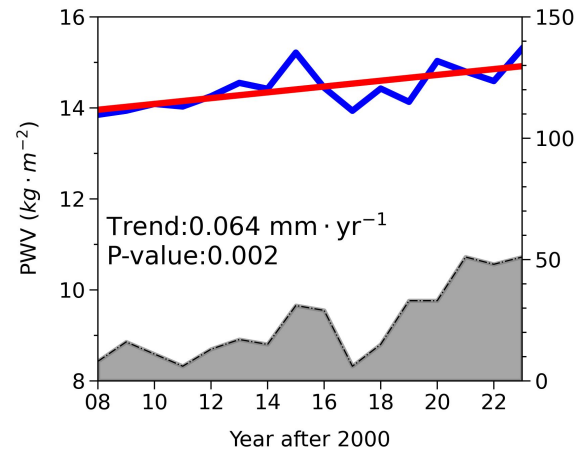
☐ Different distance bands



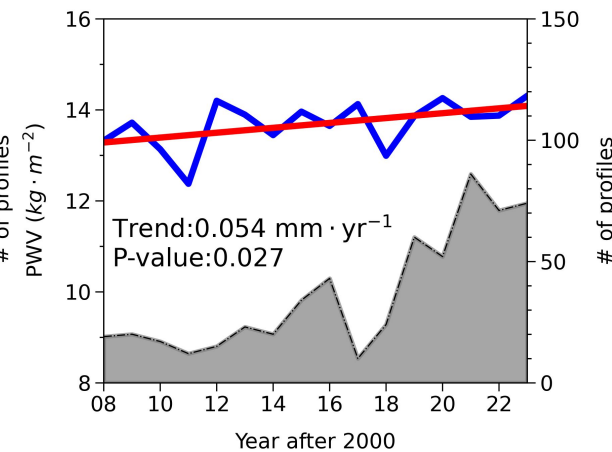
(a) WNP, 0-200 km @ 1.6-3.0 km



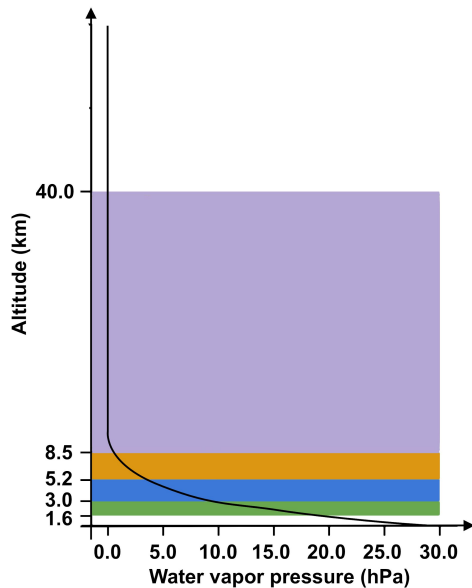
(b) WNP, 200-300 km @ 1.6-3.0 km



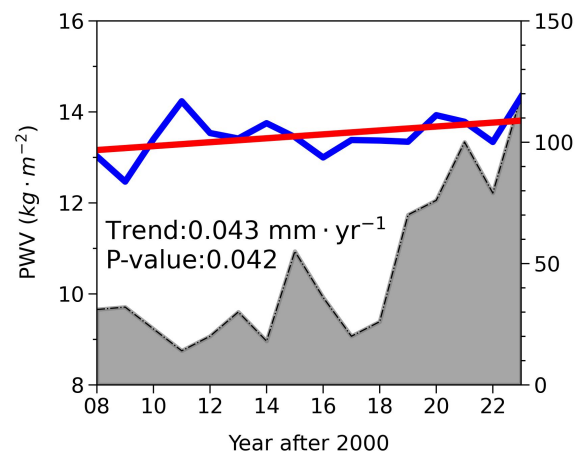
(c) WNP, 300-400 km @ 1.6-3.0 km



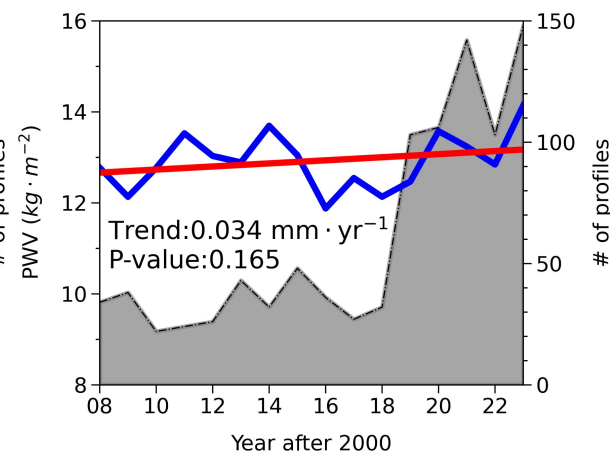
☐ Different altitude layers



(d) WNP, 400-500 km @ 1.6-3.0 km

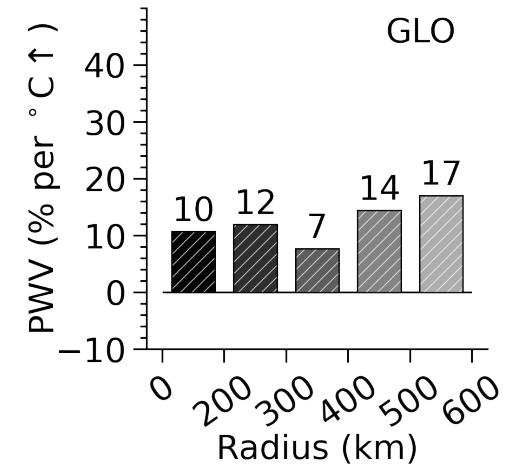
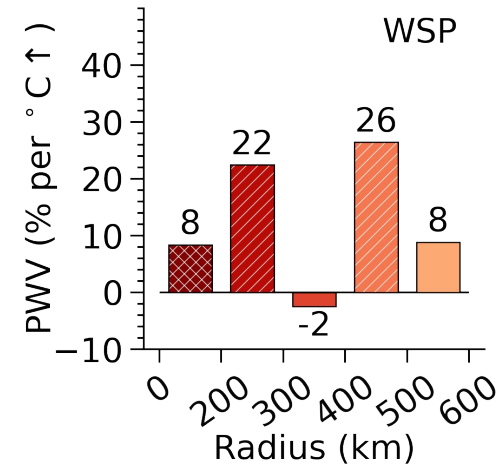
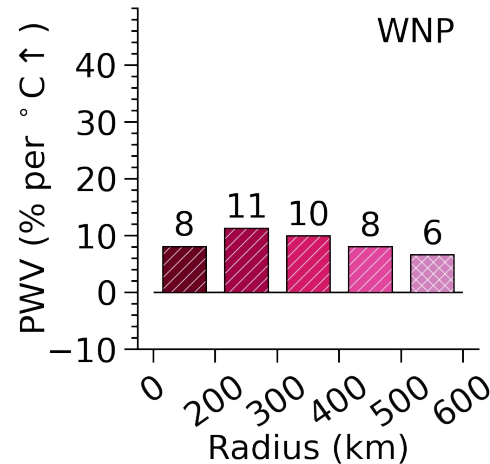
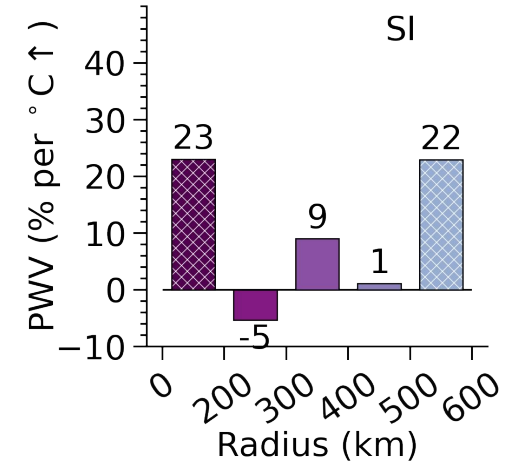
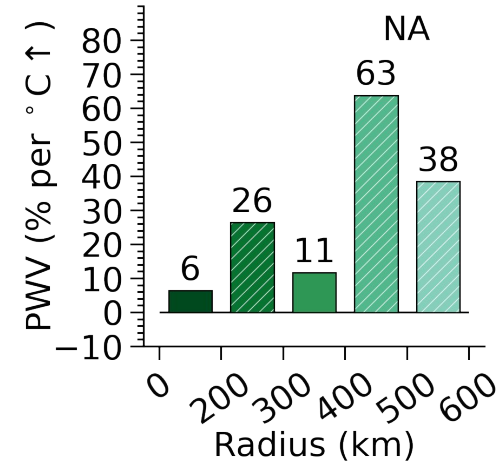
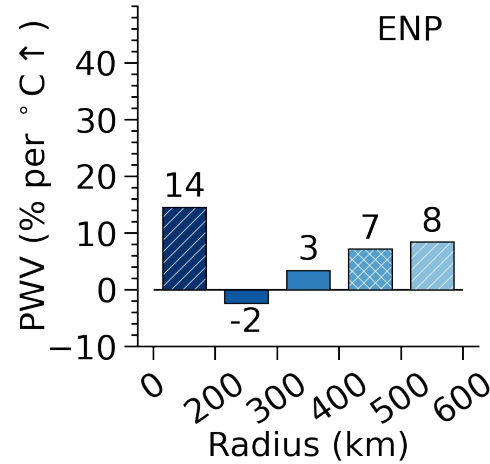




(e) WNP, 500-600 km @ 1.6-3.0 km



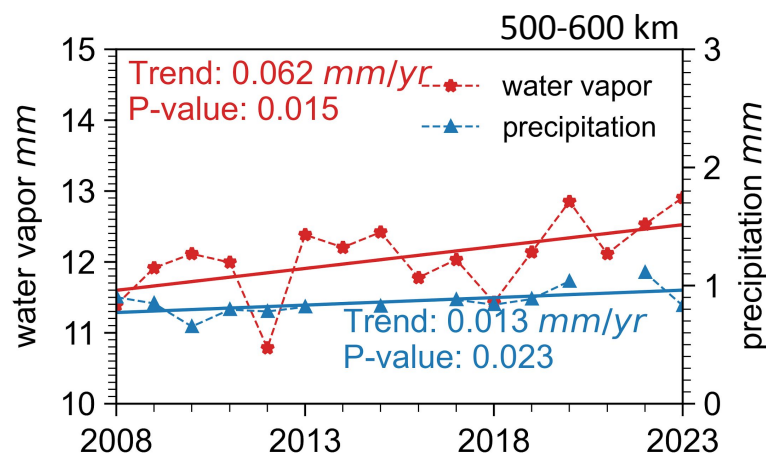
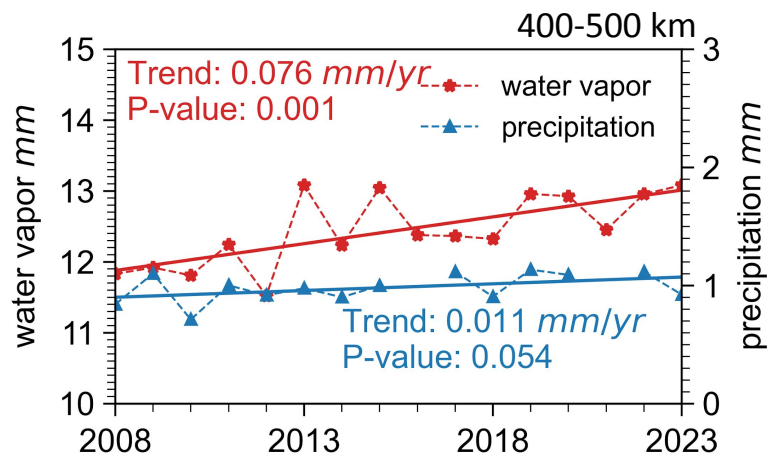
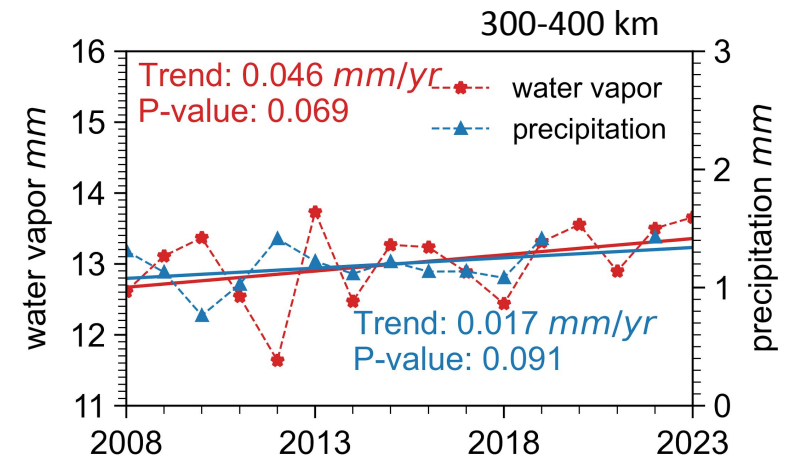
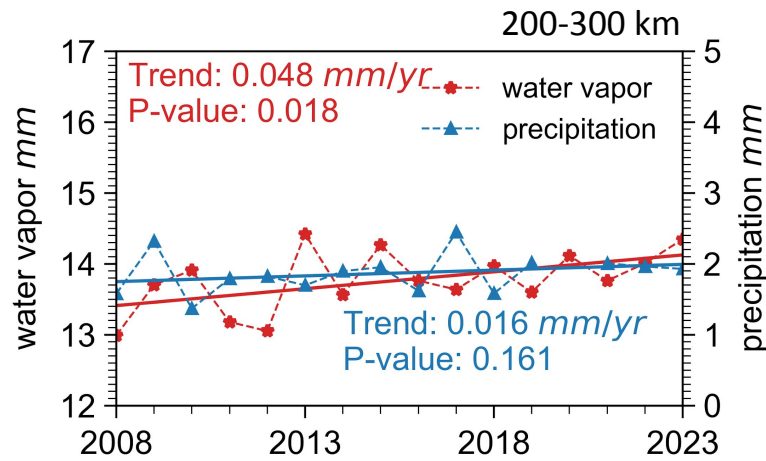
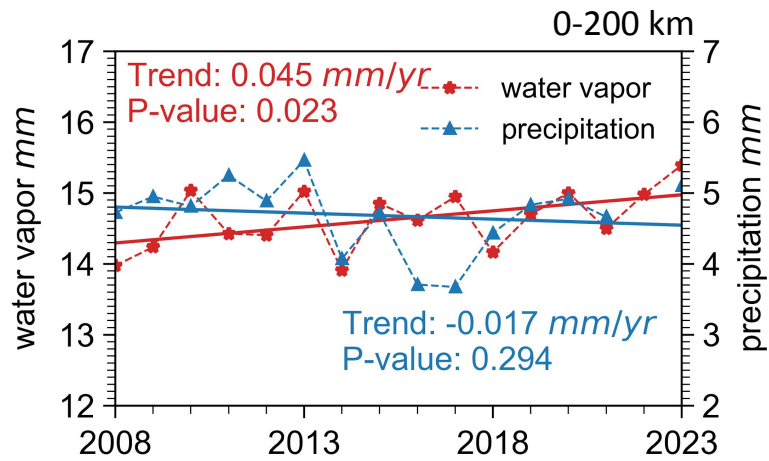
Significant increase trend of water vapor (1.6-3.0 km)

TC water vapor trend (%) responding to a 1-°C increase of corresponding air temperature. Bar with cross/slash denotes the water vapor trend is statistically significant above the 80%/90% confidence level according to a Wald's test



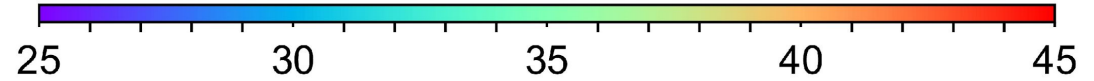
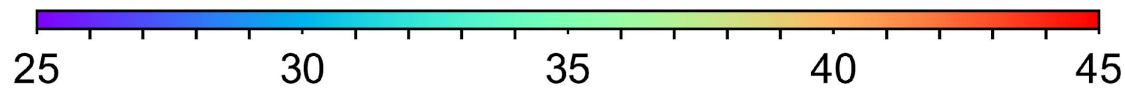
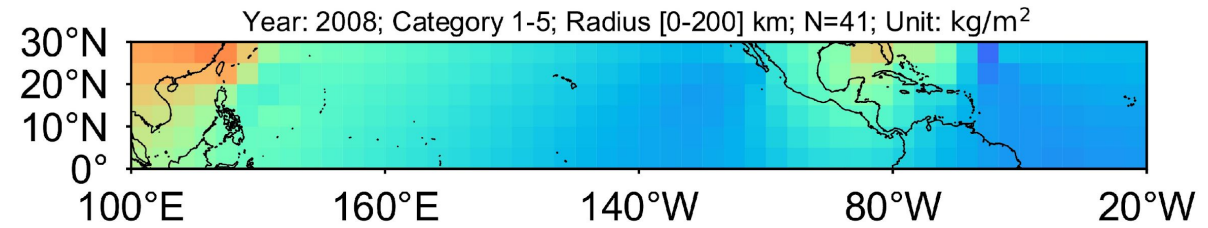
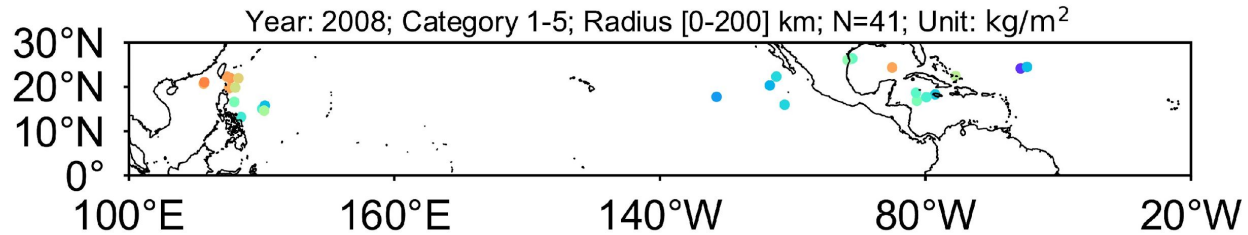
 80% confidence level
 90% confidence level

TC PWV & TP trend (different bands)



TC water vapor trend (red)
and total precipitation trend
(blue) at different bands

TC PWV & TP trend (different bands & basins)



TC PWV/TP points at bands over North Pacific Ocean and North Atlantic Ocean

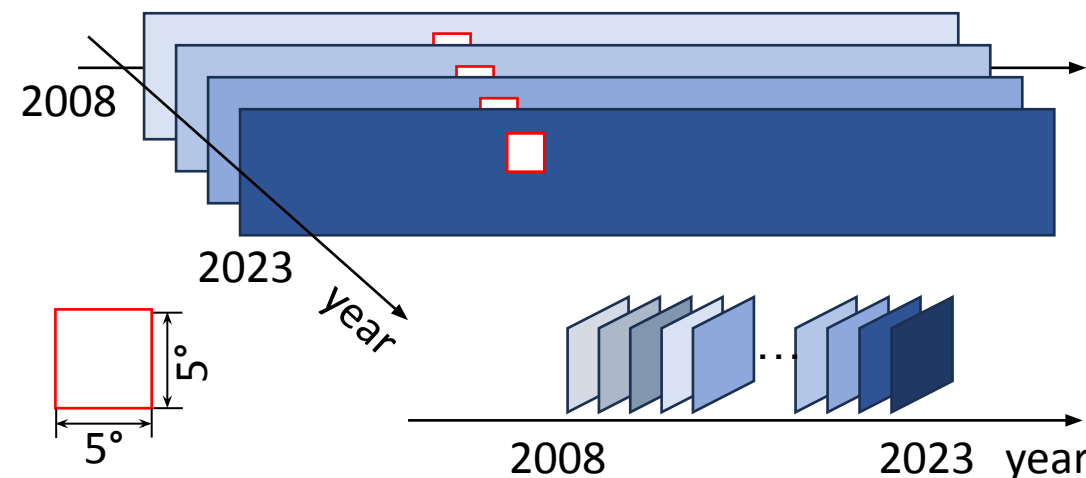
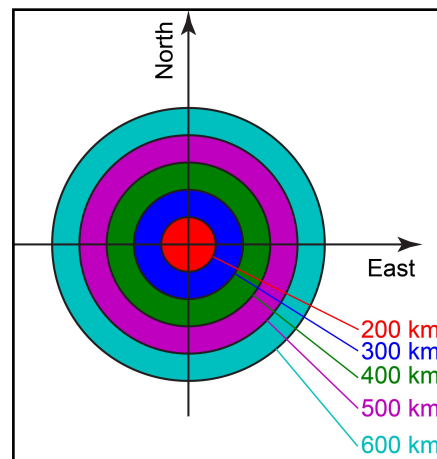
Radial basis function (RBF)
Interpolation (5°x5°)

TC PWV/TP map at bands over North Pacific Ocean and North Atlantic Ocean

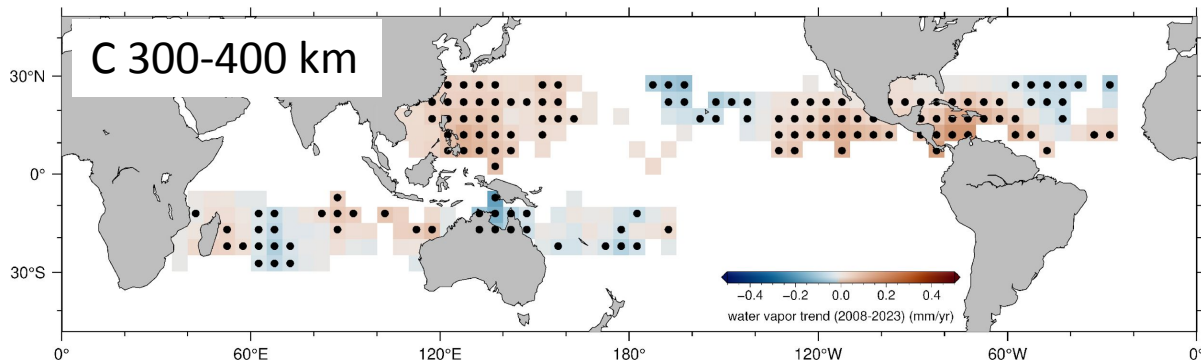
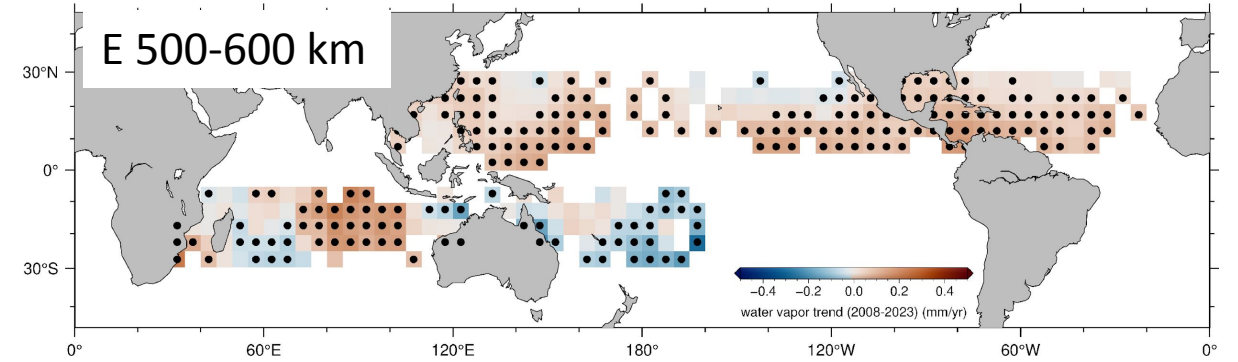
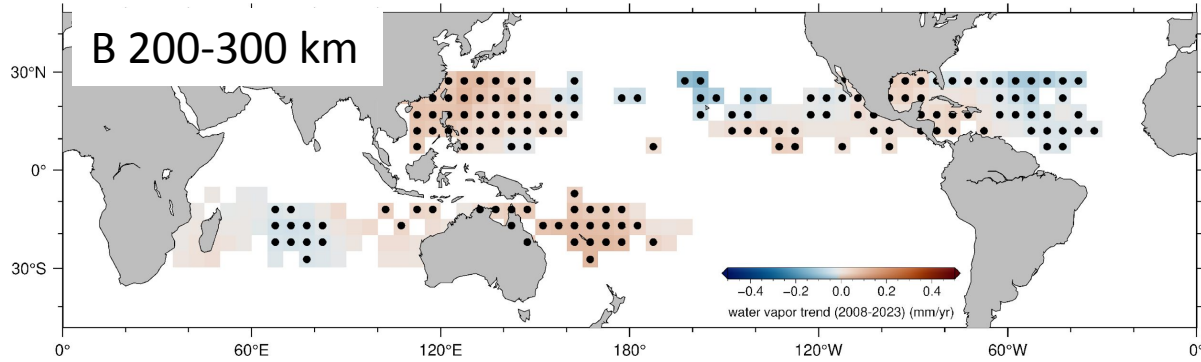
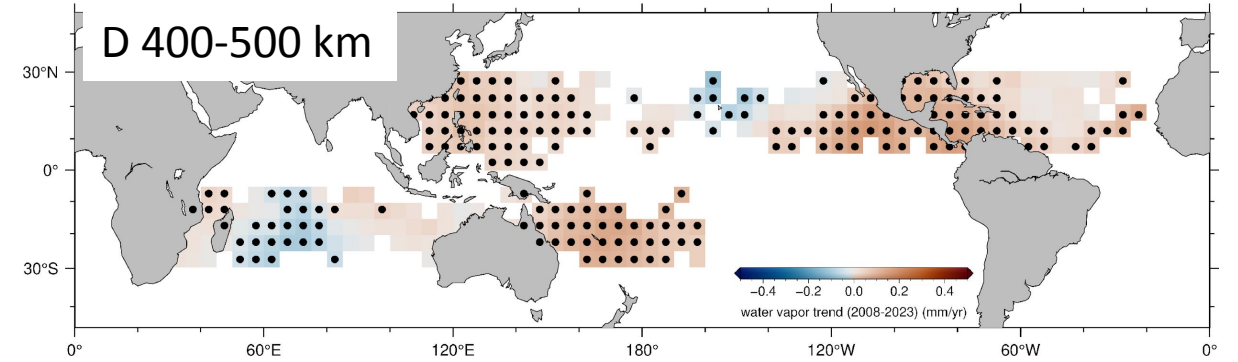
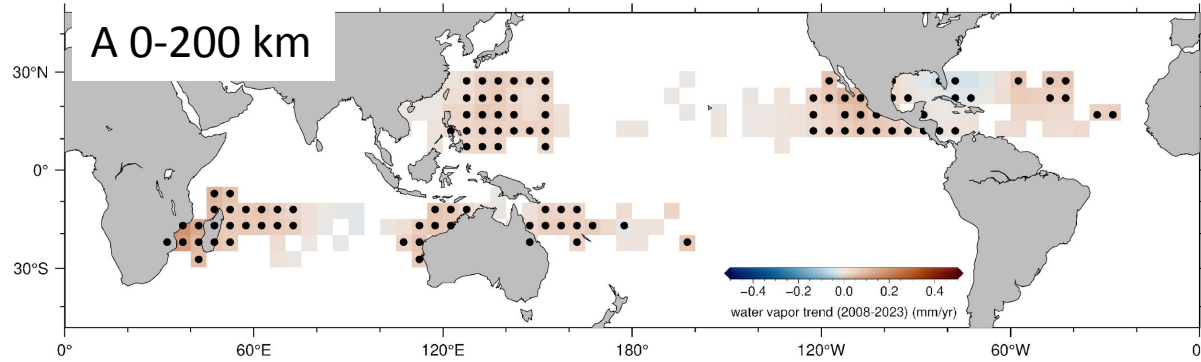
$$s(\mathbf{X}) = \sum_{i=1}^n \lambda_i \phi(\|\mathbf{X} - \mathbf{X}_i\|), \quad \mathbf{X} \in \mathbb{R}^d$$

$s(\mathbf{X})$ is the interpolant
 λ_i is the coefficients for the RBF $\phi(\|\mathbf{X} - \mathbf{X}_i\|)$
 which can be simplified as $\phi(r)$

$$\phi(r) = r, \quad \text{Linear RBF function}$$

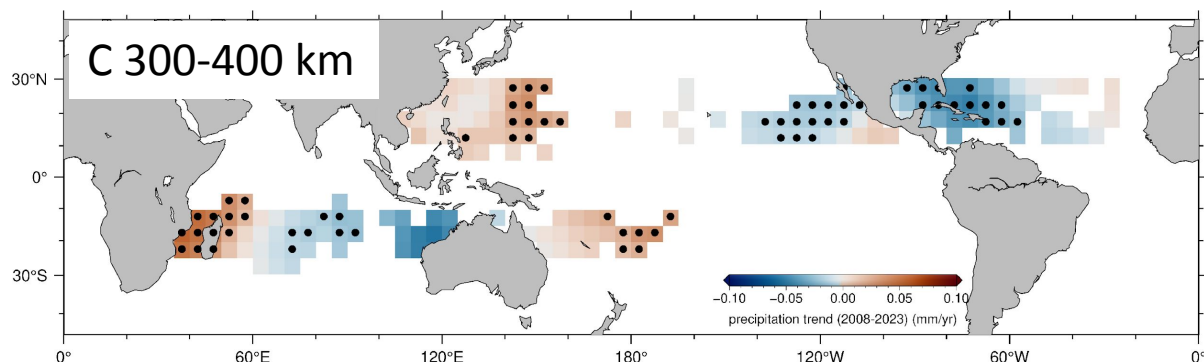
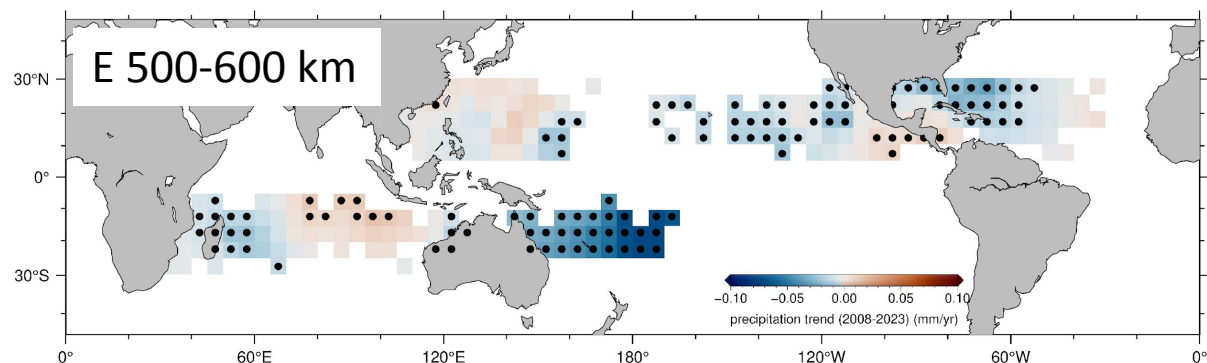
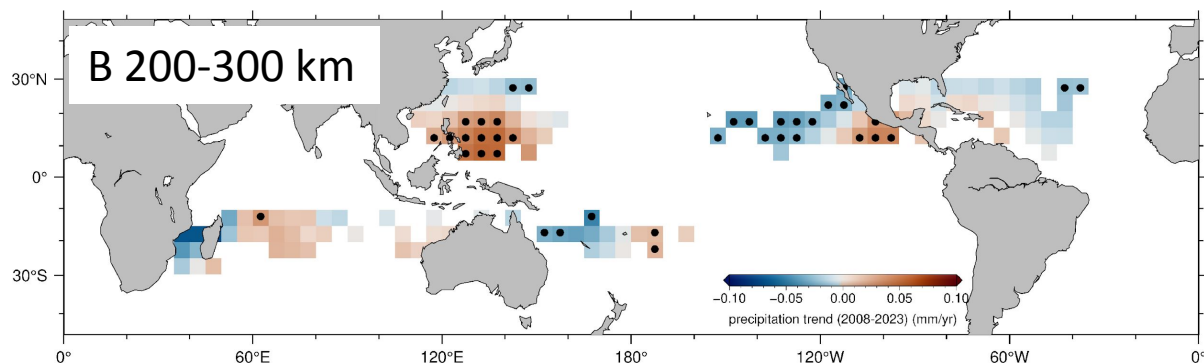
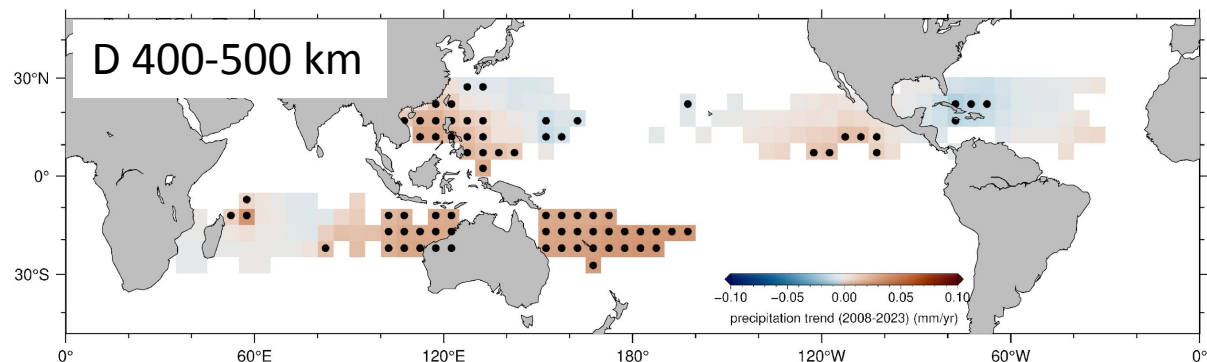
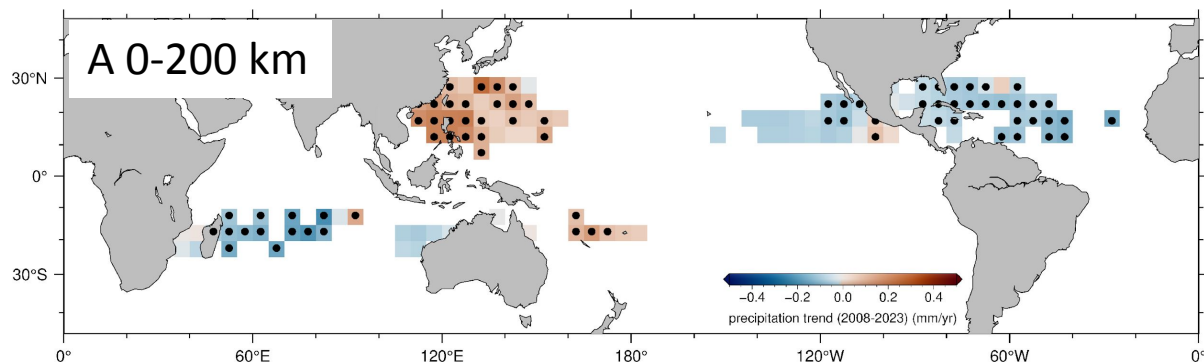


TC water vapor trend (different bands)



PWV trend at grids with spatial resolution of $5^\circ \times 5^\circ$ in latitude and longitude. The black dots in PWV trend indicates the linear trend over the grid cell is **statistically significant at the 95% level** according to the Wald significance test with t-distribution

TC total precipitation trend (different bands)



Total precipitation (TP) trend at grids with spatial resolution of $5^\circ \times 5^\circ$ in latitude and longitude. The black dots in PWV trend indicates the linear trend over the grid cell is **statistically significant at the 80% level** according to the Wald significance test with t-distribution

Conclusion

- ❑ Globally, the SST increases by 0.02 °C per year, and water vapor increases by 0.05 mm per year.
- ❑ TC Mixing ratio @ 1.6-3.0 km increases by 0.03 g/kg per year (7.8% per year) , correspondingly.
- ❑ TC Water vapor @ 1.6-3.0 km increases by ~12% for 1-°C increase in air temperature
- ❑ Changes of TC total precipitation is not consistent with the change of water vapor.



CliMet

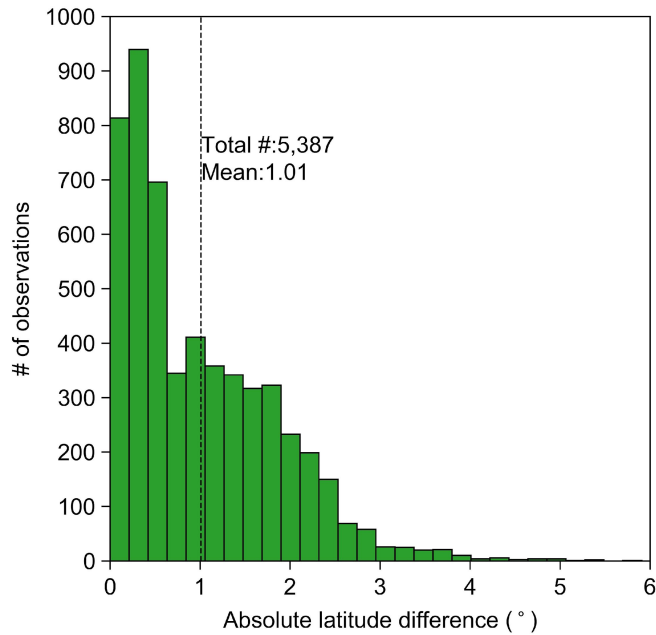


Thank you!

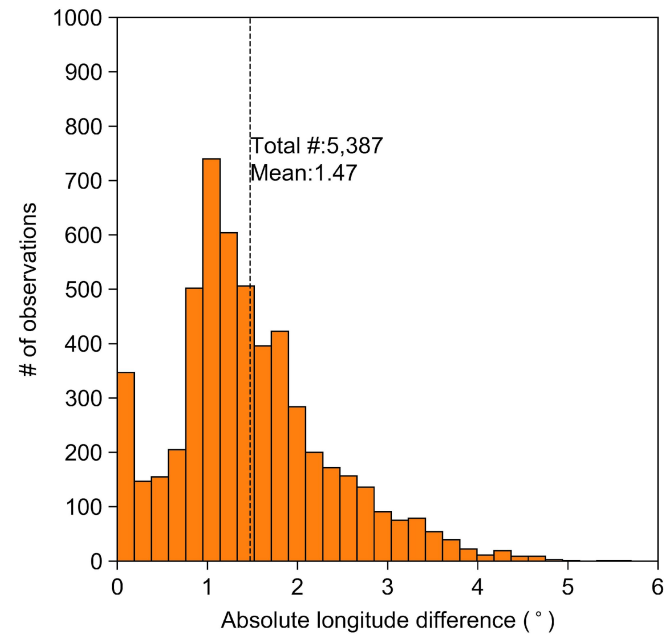
jessellyu@ust.hk

cehsu@ust.hk

GNSS RO data properties (backup)

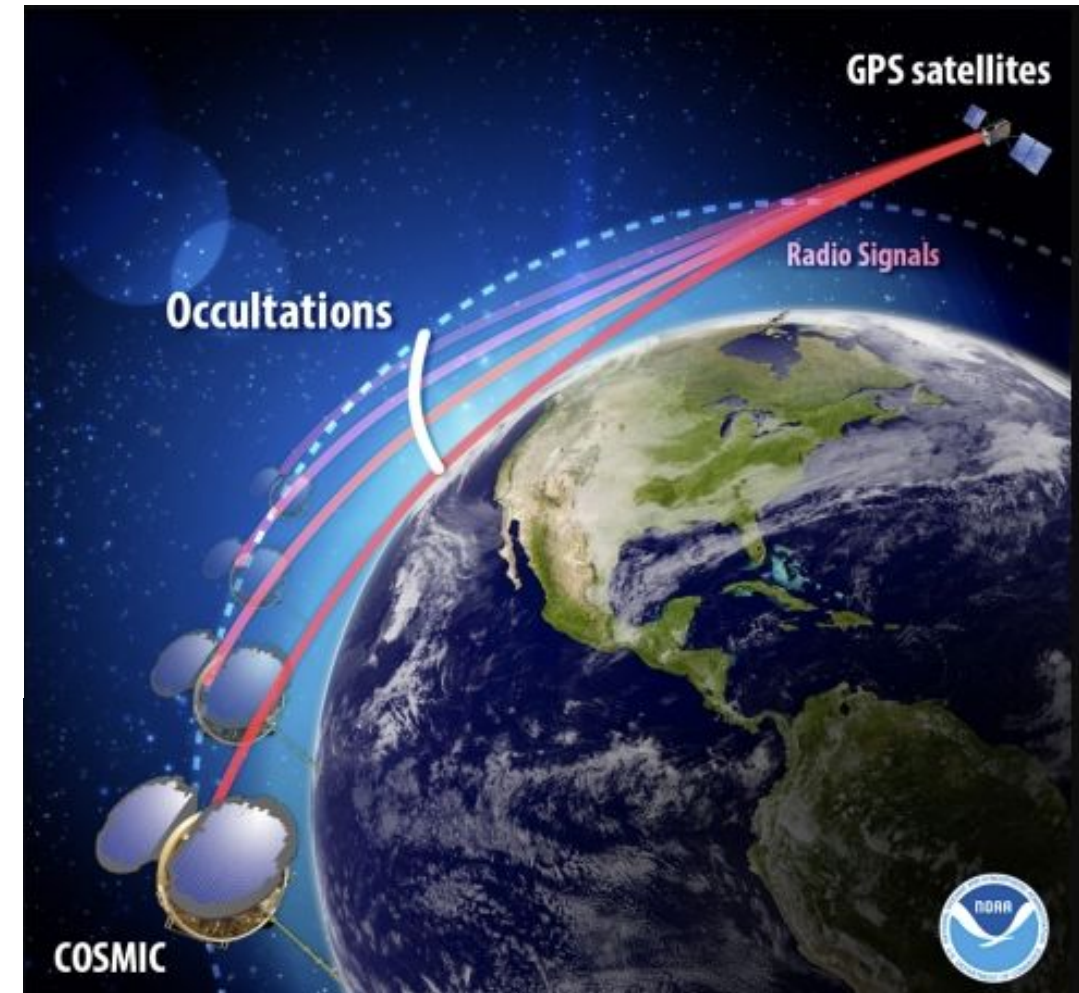


Latitude: 1.01°

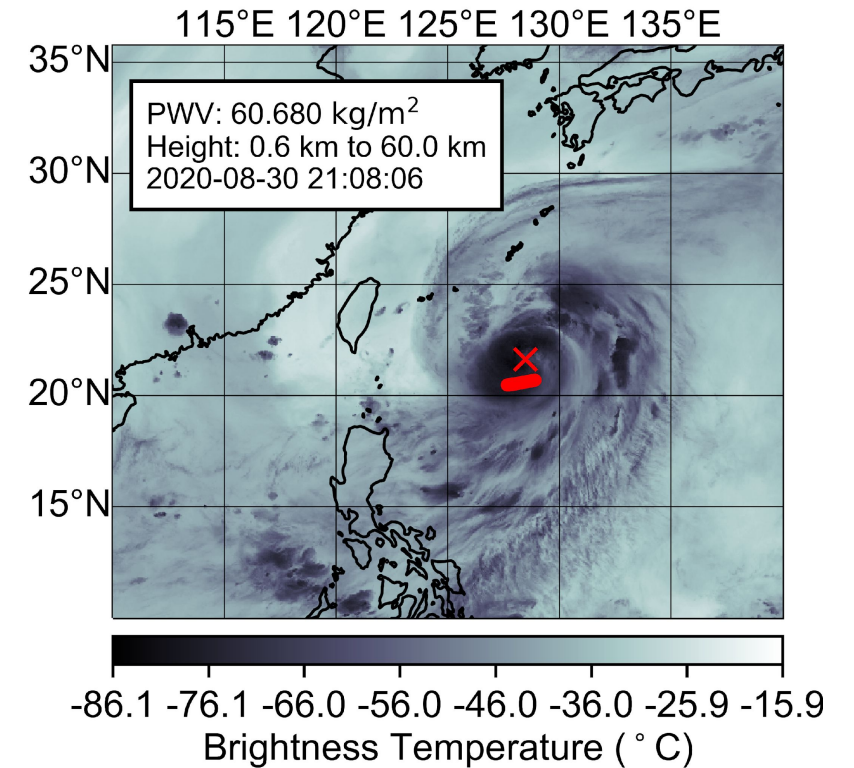
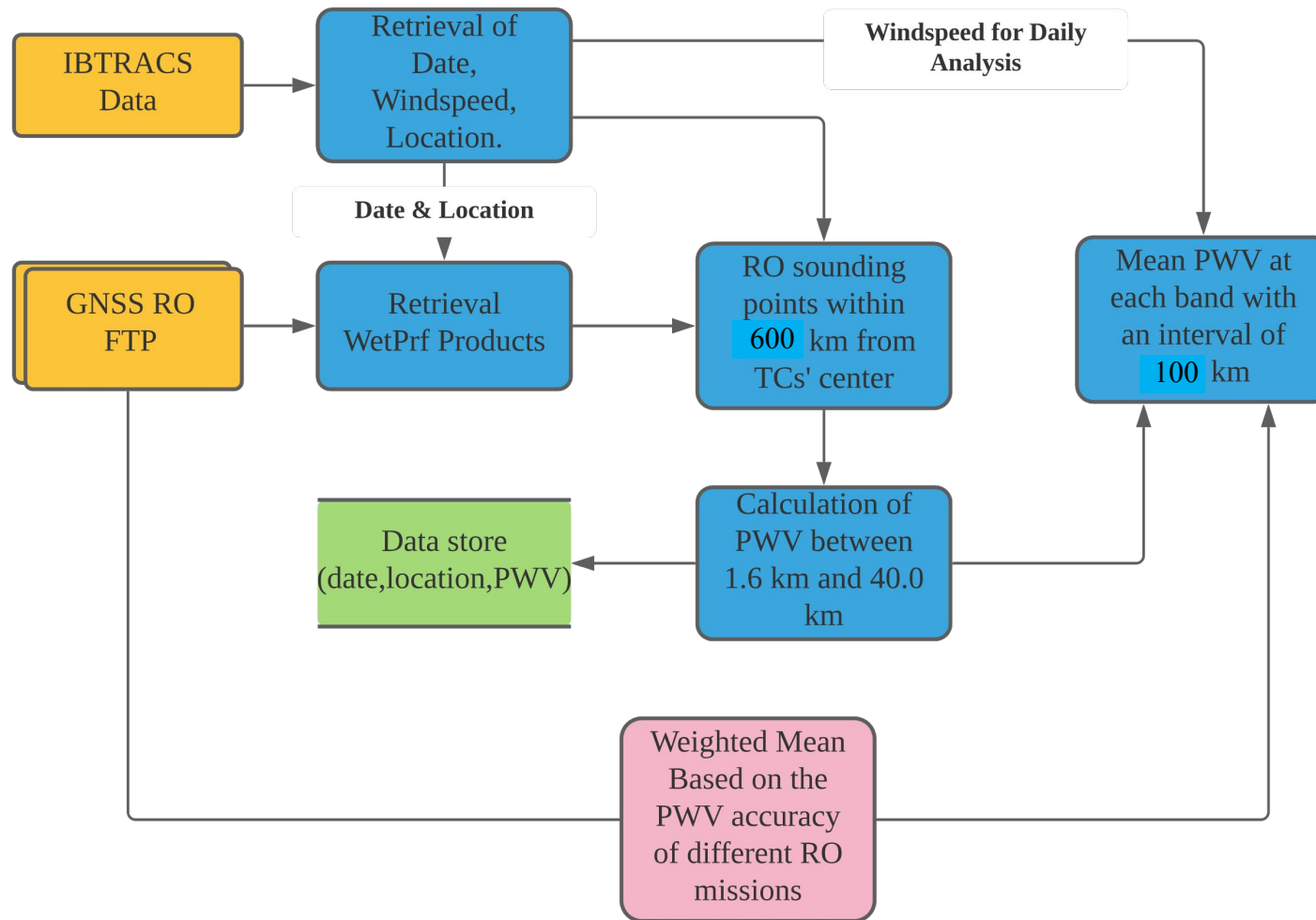


Longitude: 1.47°

Horizontal shift between the first and last sounding point of each RO profile (5,387 in total) in latitude and longitude



GNSS RO data processing (backup)



TC PWV trend from ERA5 (backup)



Legend

—▶ RO

—▶ ERA5

