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The impact of turbulence, clouds, and dynamic processes on precipitation and air quality over South America

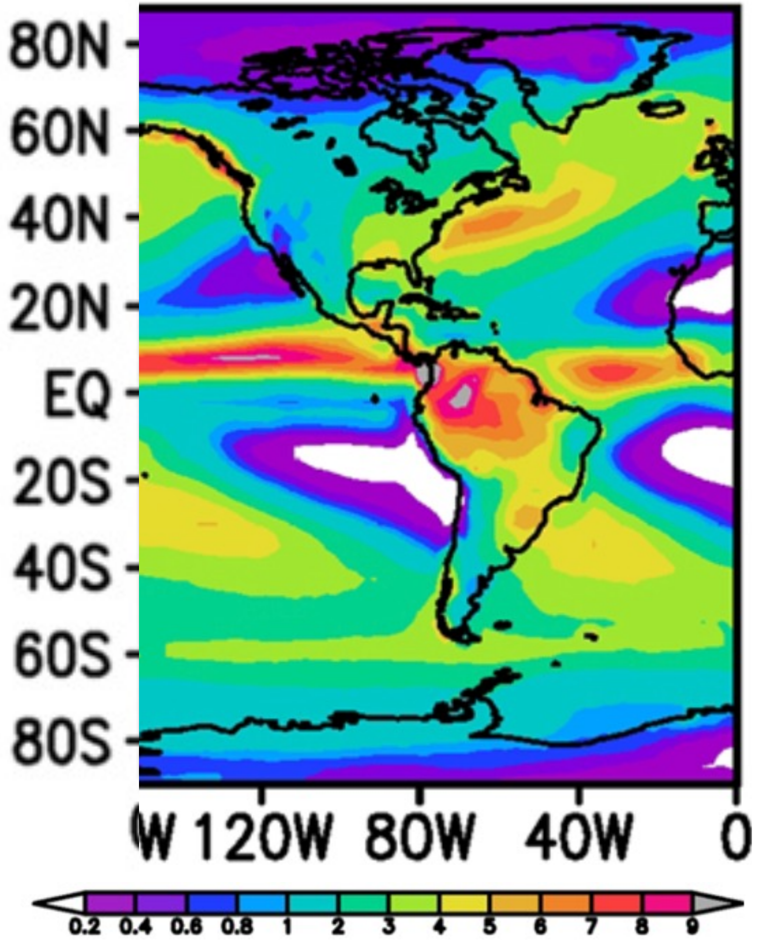
Xiao-Ming Hu
Center for Analysis and Prediction of Storms (CAPS),
University of Oklahoma

July 2024

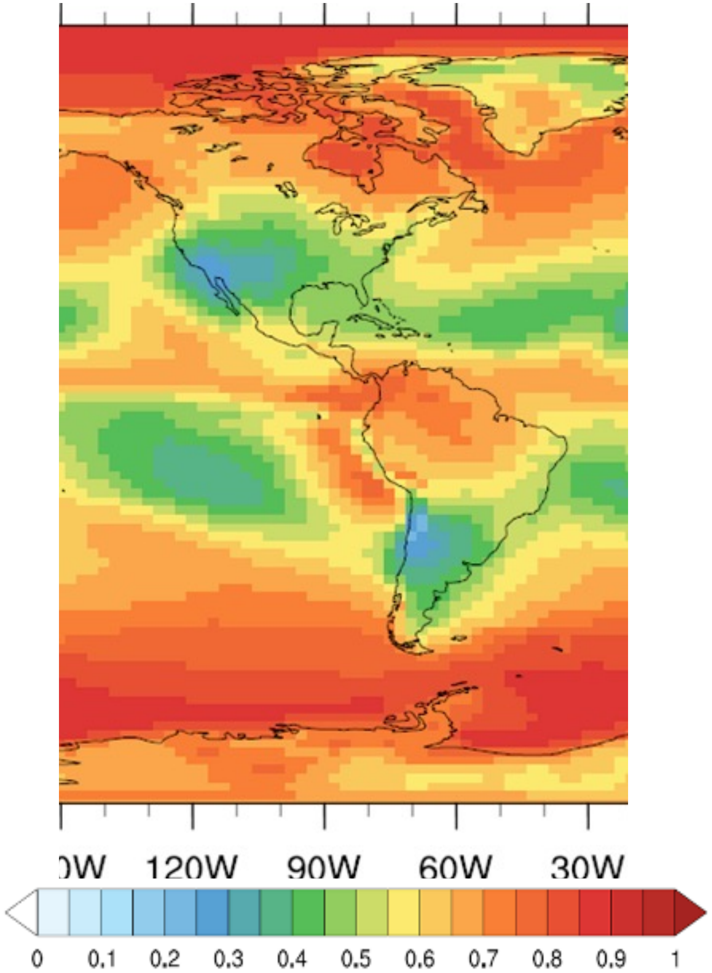
UNSA

Annual mean precipitation and clouds

Annual mean precipitation during 1979–2014



mean cloud fraction 2000-2020

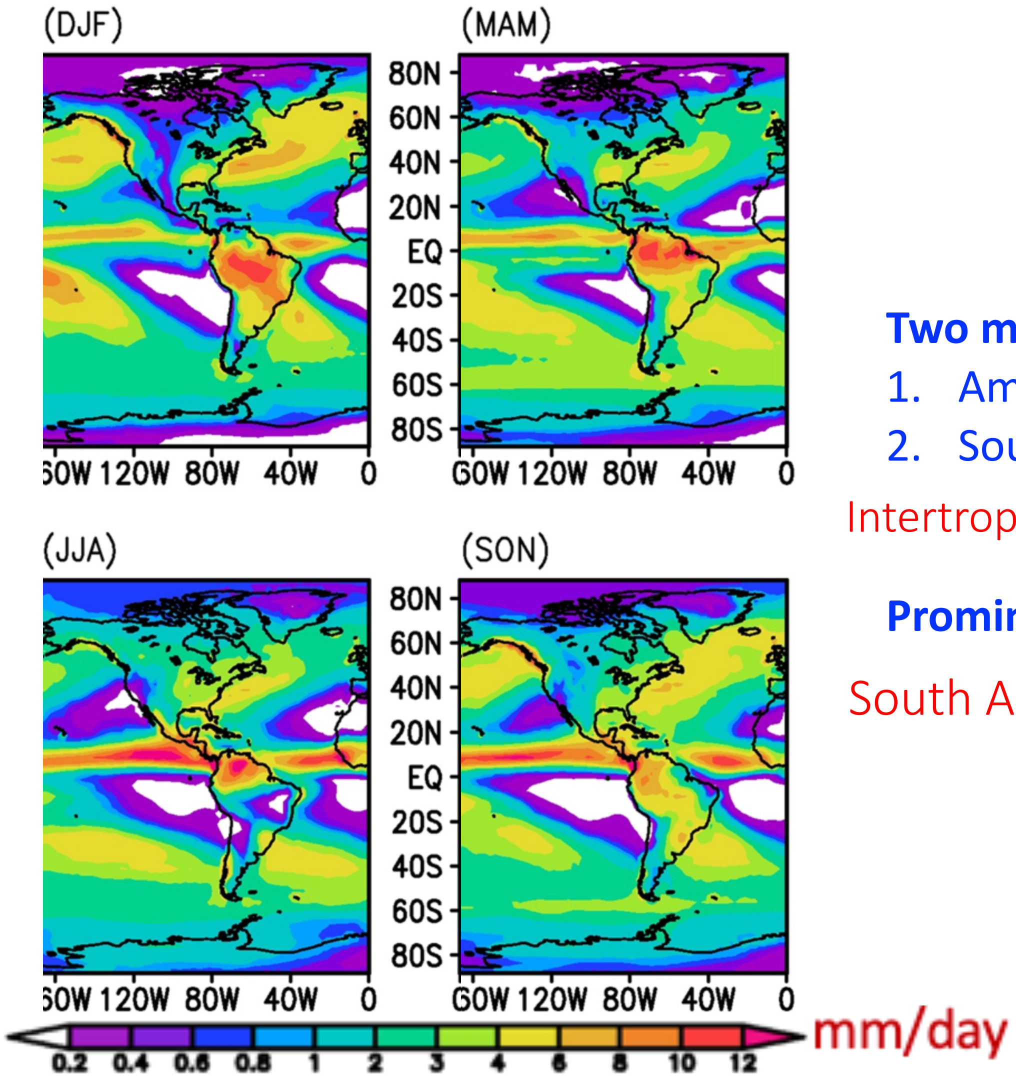


https://doi.org/10.1007/s10712-017-9416-4

Precipitation and cloud processes are prominent over South America

Precipitation/clouds/turbulence/dynamic processes are entangled

Seasonal mean precipitation during 1979–2014



https://doi.org/10.1007/s10712-017-9416-4

Two major precipitation regions over South American:

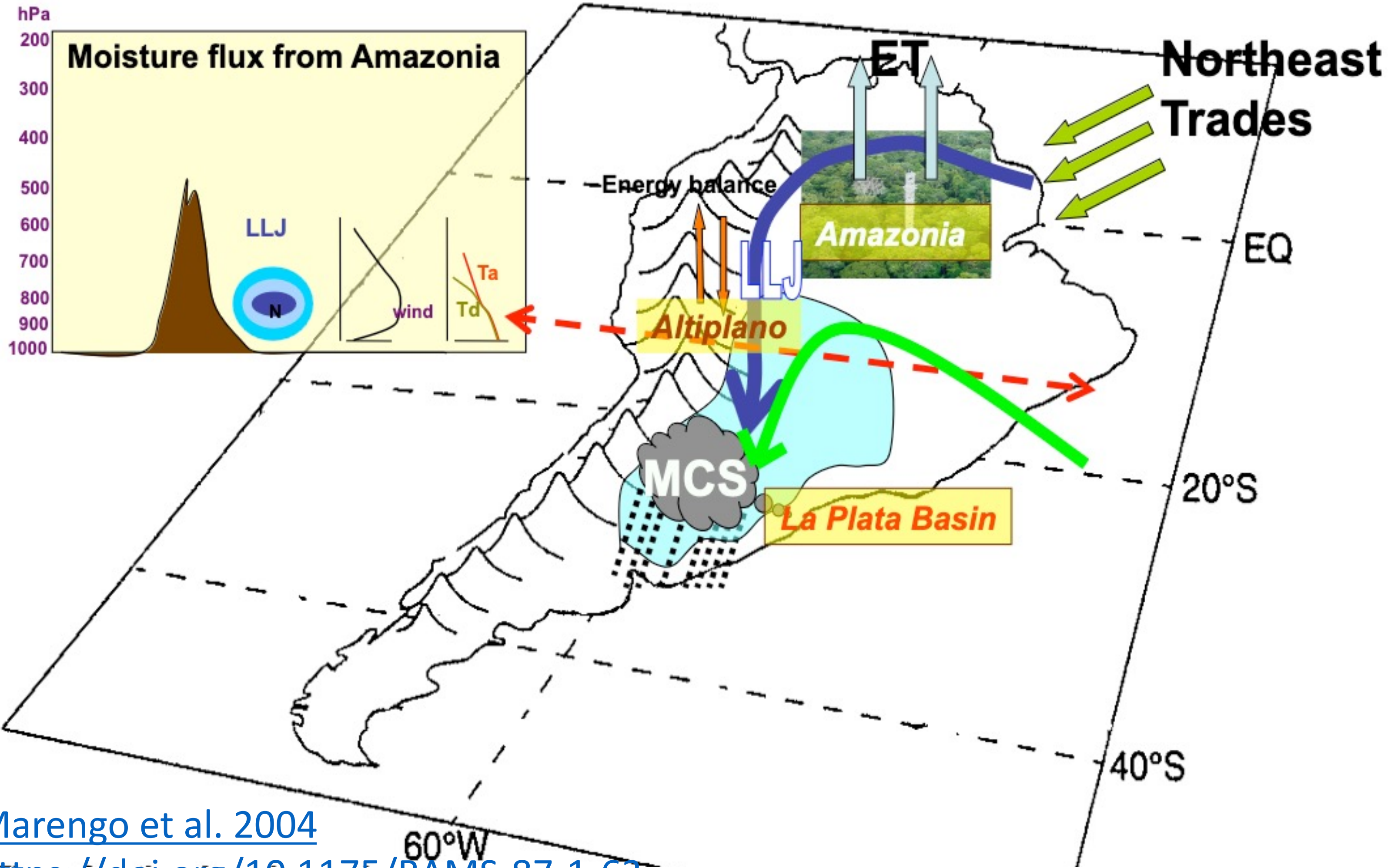
1. Amazon
2. Southeastern South America (SESA)

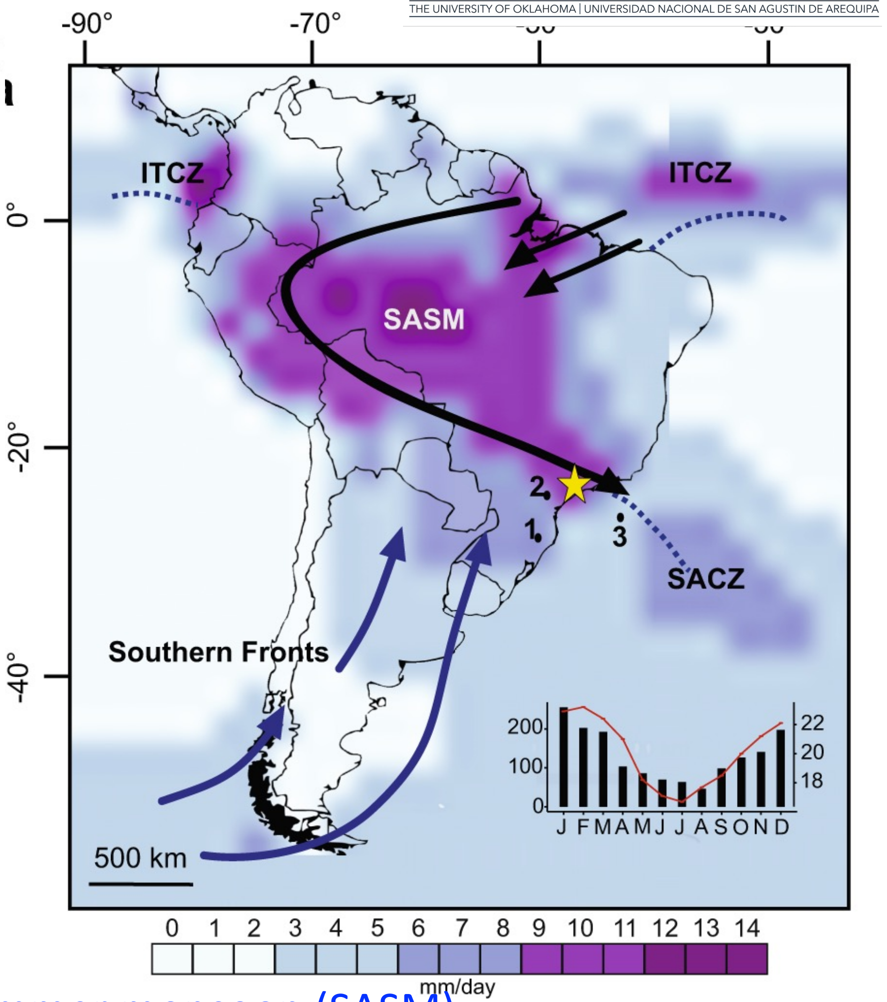
Intertropical and South Atlantic convergence zones (ITCZ and SACZ)

Prominent seasonal variation, wet season vs. dry season

South American summer monsoon (SASM)

Low-level atmospheric circulation over South America





Marengo et al. 2004
https://doi.org/10.1175/BAMS-87-1-63
Rodríguez-Zorro et al. https://rdcu.be/c730B

South American summer monsoon (SASM)
Intertropical and South Atlantic convergence zones (ITCZ and SACZ)

Sensitivity of summer precipitation to PBL schemes

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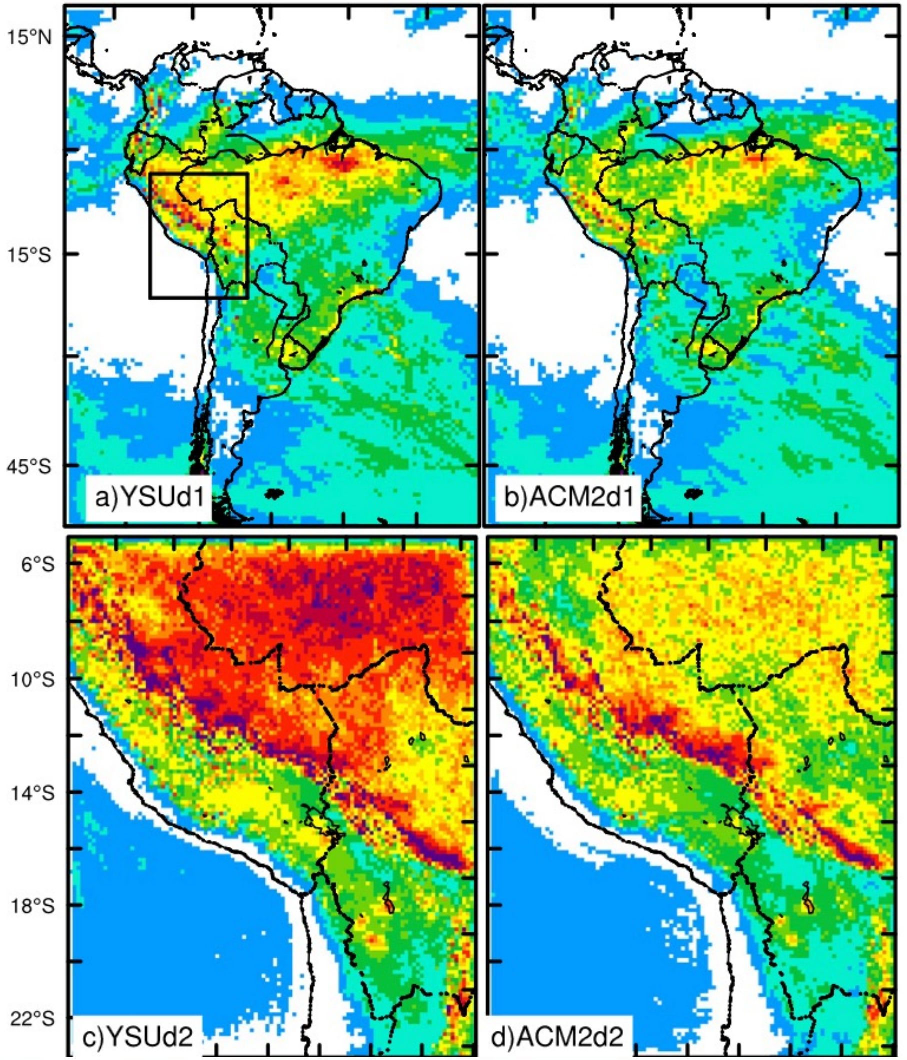
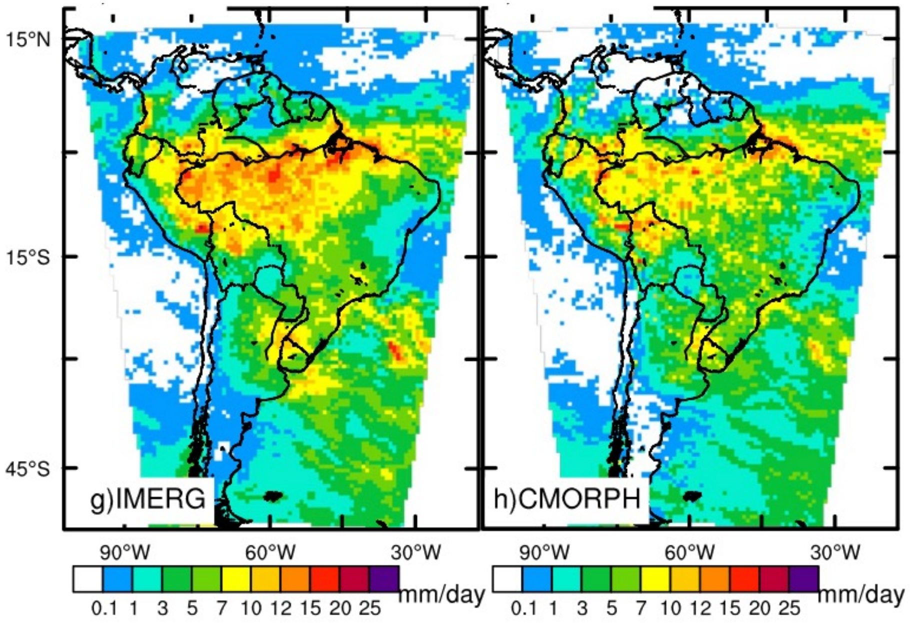
YSU ACM2



Observations



- YSU boundary layer scheme simulates stronger precipitation

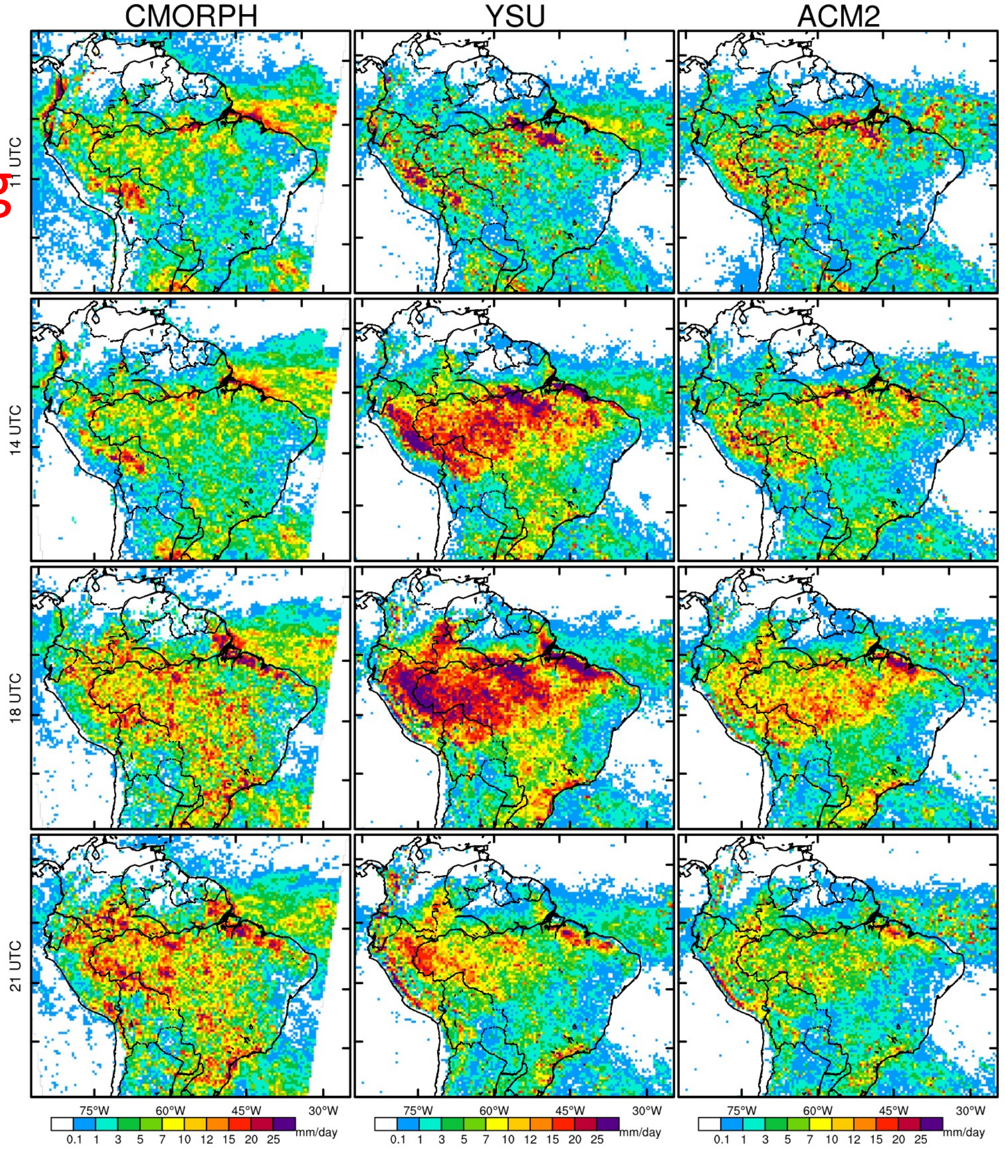
Hu, X.-M., Y. Huang, M. Xue, E. Martin, Y. Hong, M. Chen, H. M. Novoa, et al., Effects of lower troposphere vertical mixing on simulated clouds and precipitation over Amazon during the wet season. *J. Geophys. Res.-Atmospheres*, 10.1029/2023JD038553 .

Evaluate diurnal variation of precipitation

Early morning

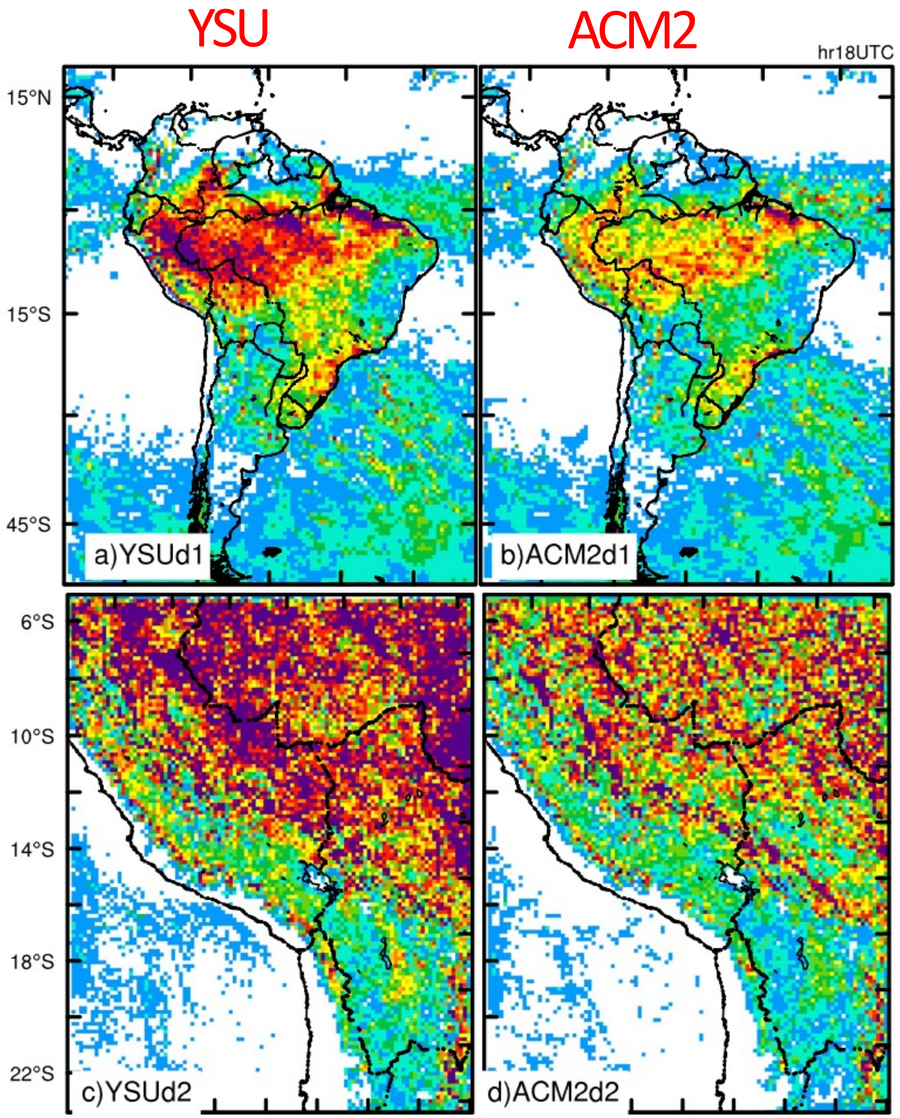
Daytime

Nighttime

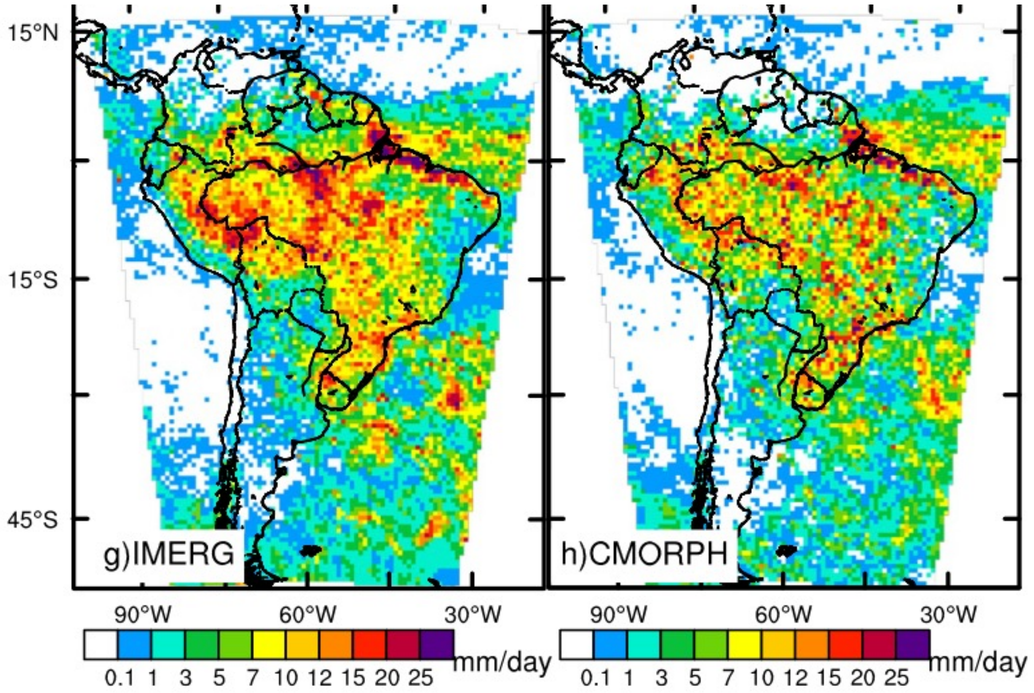


- YSU simulates stronger daytime precipitation

Sensitivity of noontime precipitation to PBL schemes

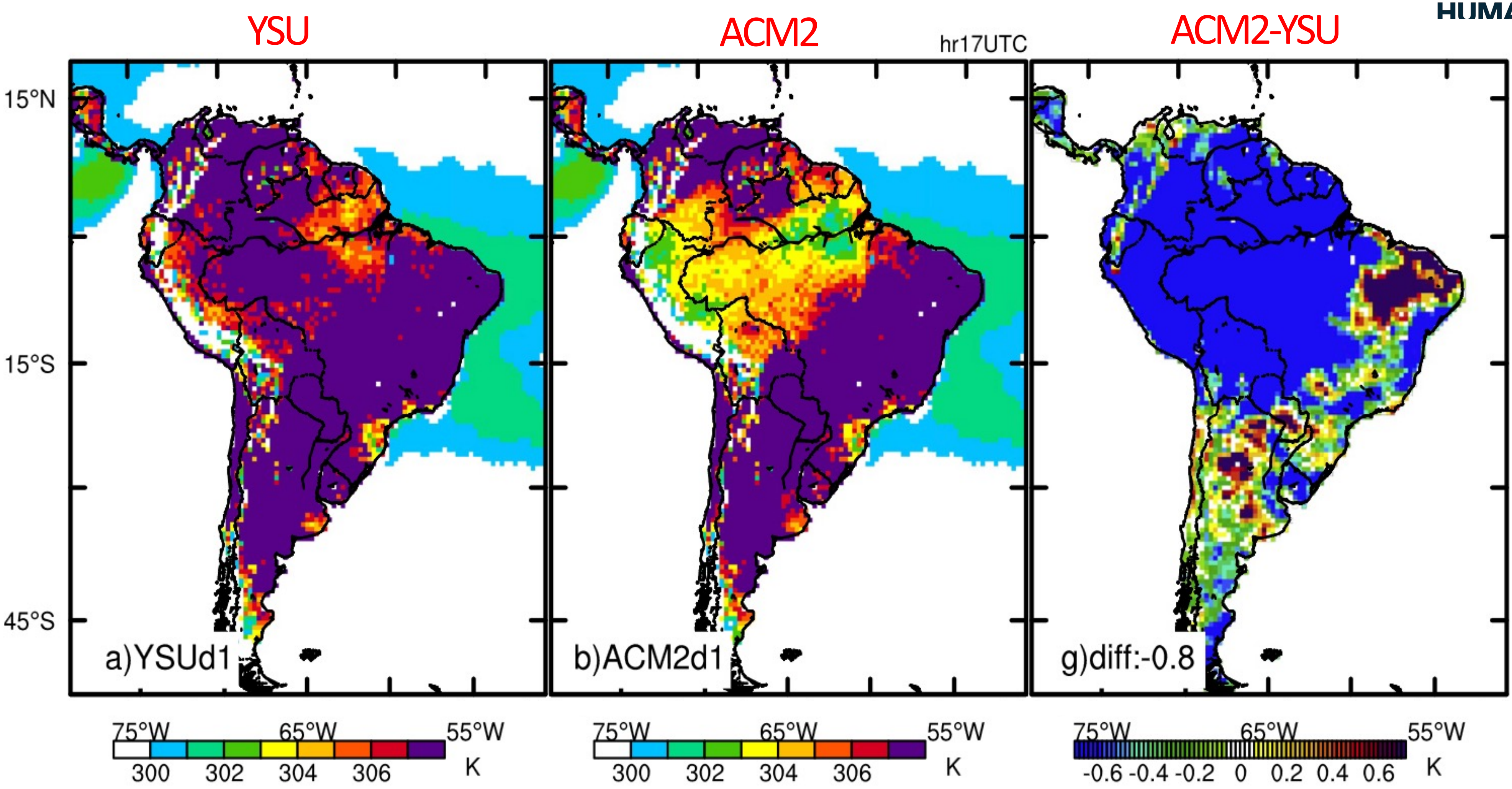


Observations



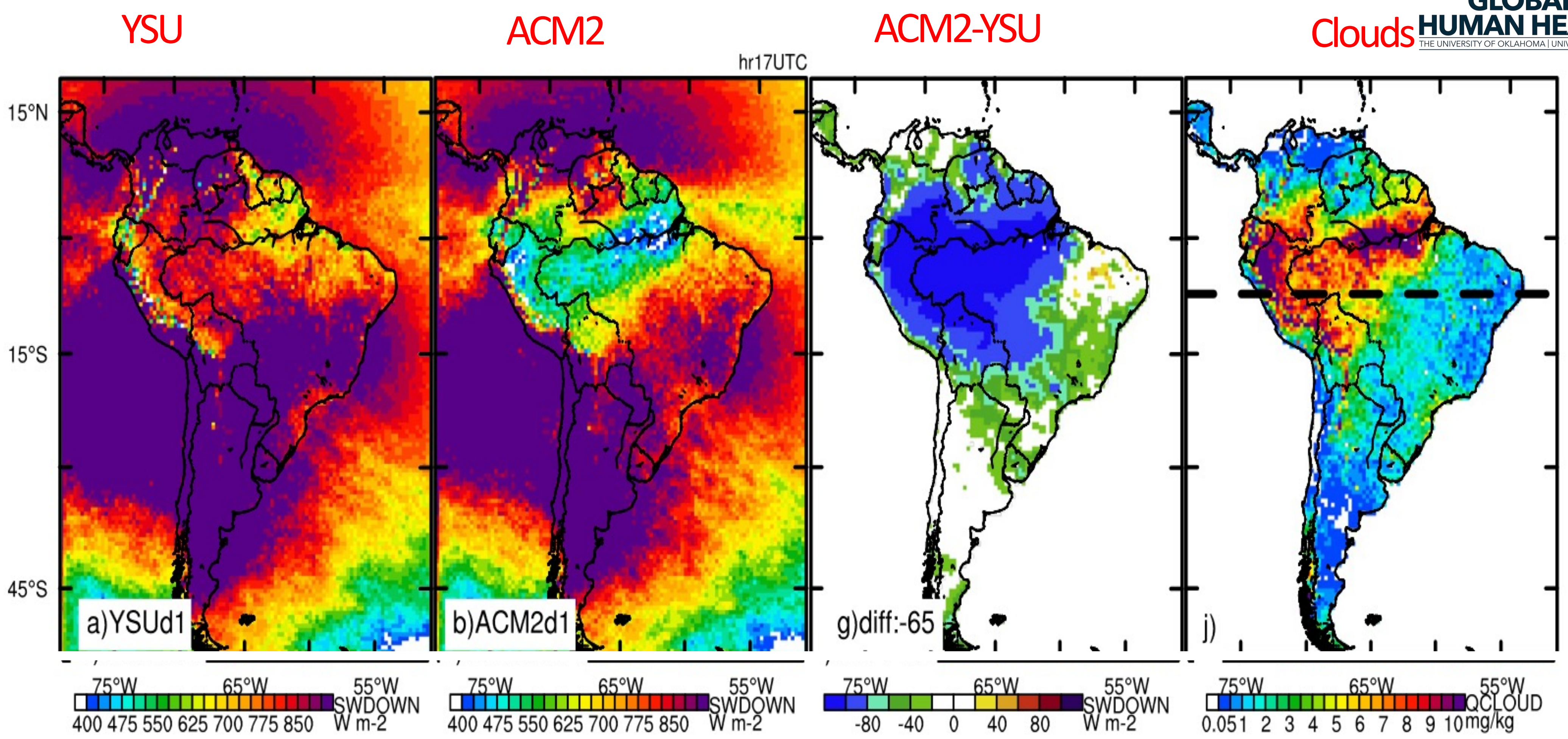
- YSU overestimates daytime precipitation

Sensitivity of noontime temperature to PBL schemes



- YSU simulates higher daytime temperature

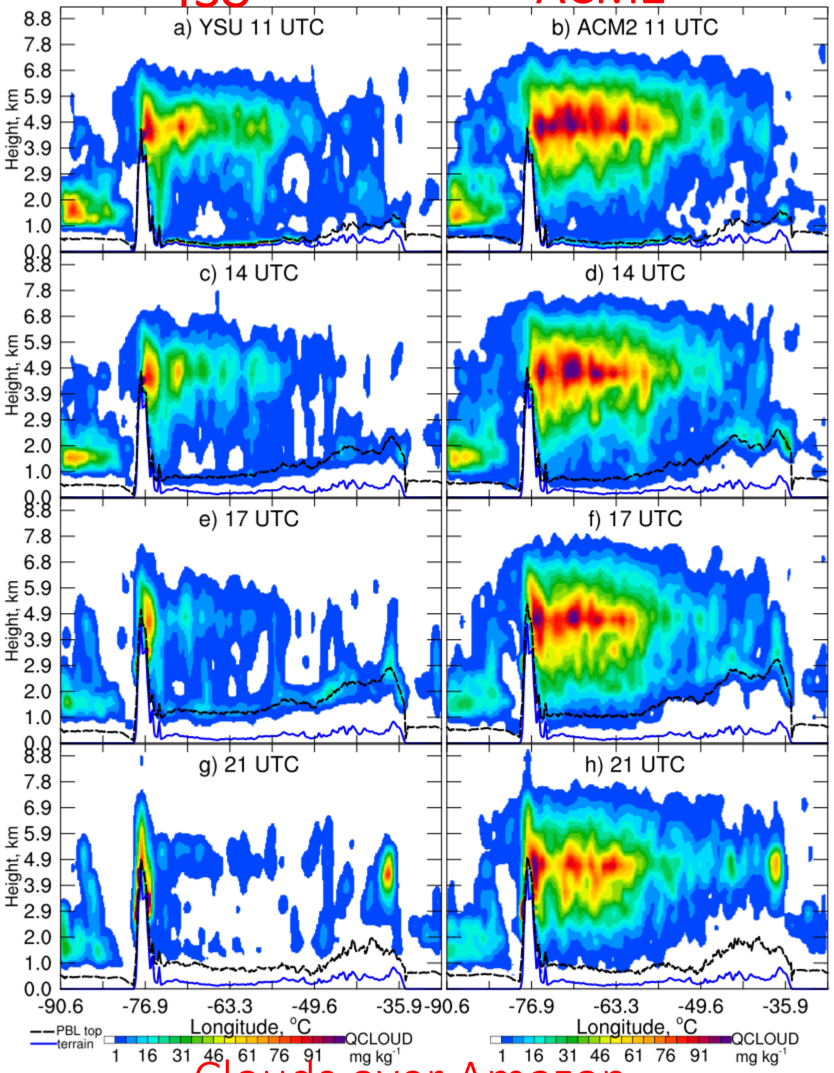
Sensitivity of noontime radiation to PBL schemes



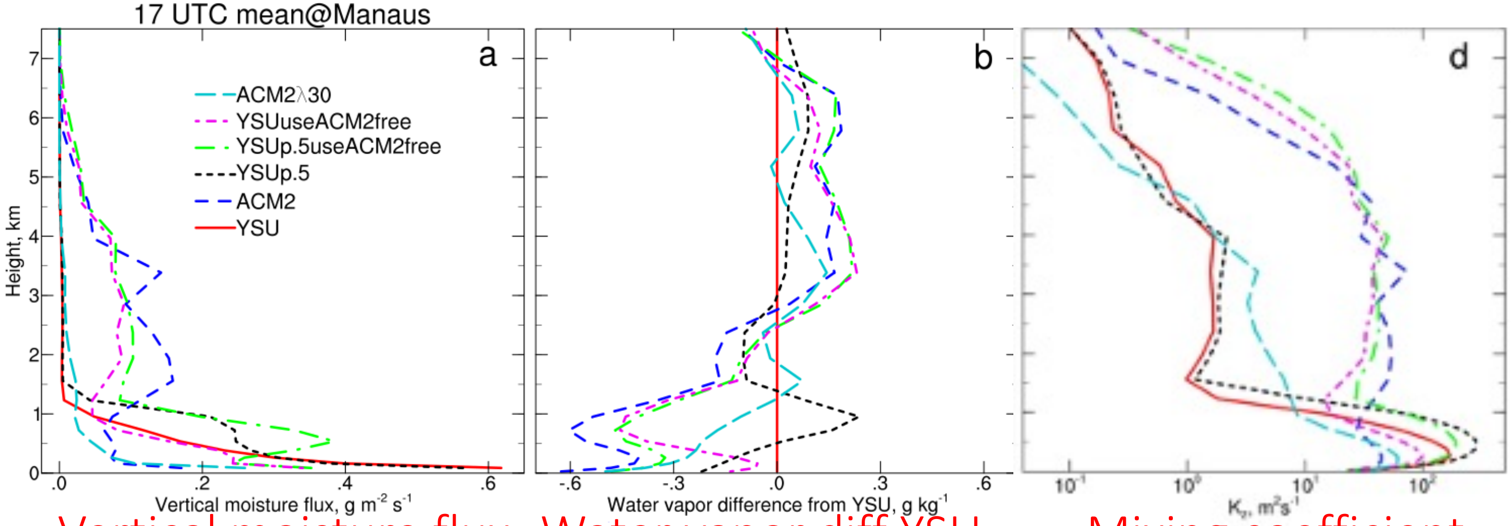
- YSU simulates stronger daytime radiation over **cloud region**

Diurnal variation of clouds: YSU vs. ACM2

YSU ACM2



Clouds over Amazon



Vertical moisture flux   Water vapor diff YSU   Mixing coefficient

- Clouds dissipate during the day in YSU runs while they maintain in ACM2 runs
- ACM2 boundary layer scheme simulates more clouds by mixing more moisture upwards.

Hu, X.-M., Y. Huang, M. Xue, E. Martin, Y. Hong, M. Chen, H. M. Novoa, et al., [Effects of lower troposphere vertical mixing on simulated clouds and precipitation over Amazon during the wet season.](#) *J. Geophys. Res.-Atmospheres*, [10.1029/2023JD038553 .](#)

Detailed Analyses to Understand How Boundary Layer/turbulent Scheme Affects Rainfall in Amazon Region

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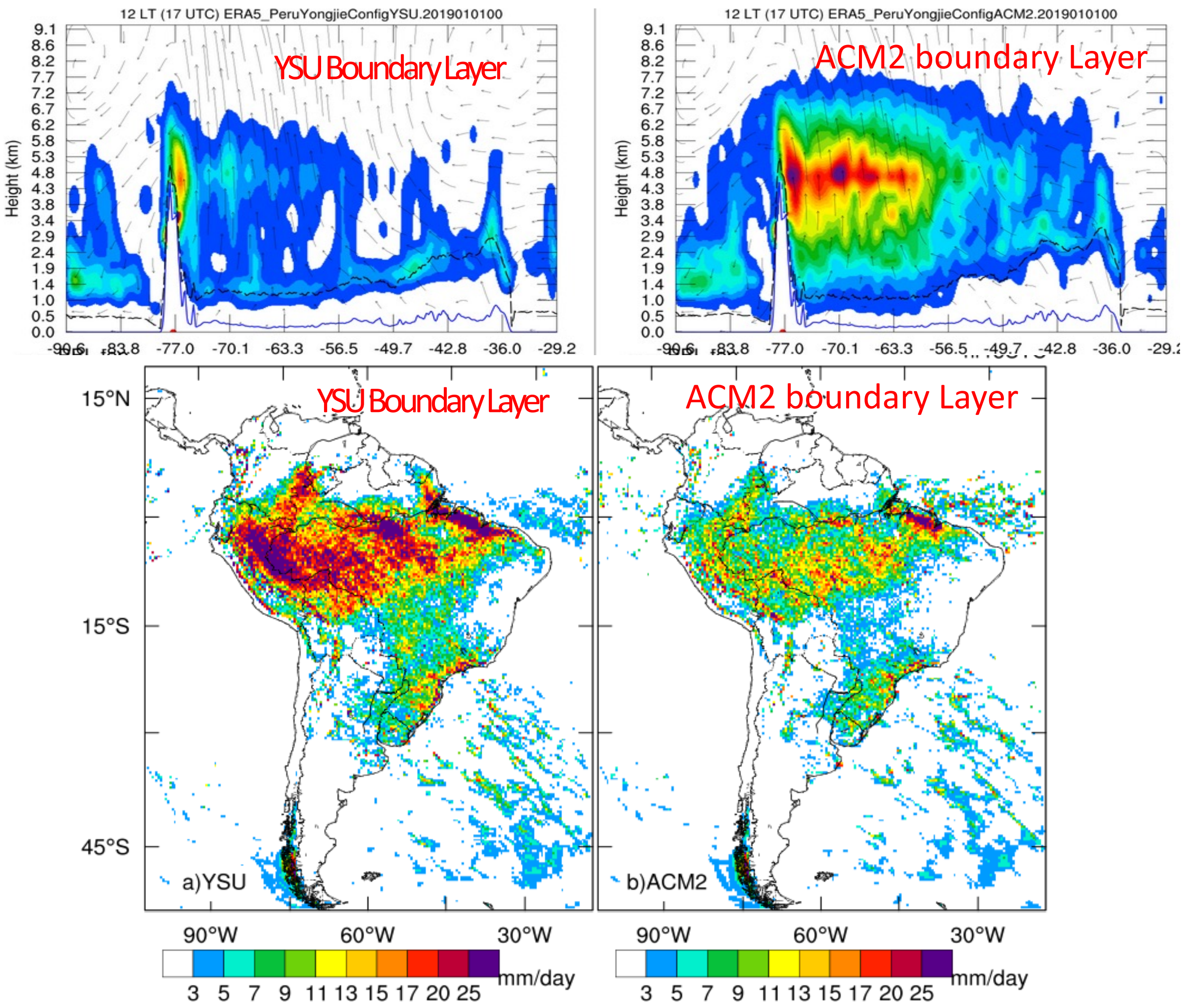
Clouds over Amazon

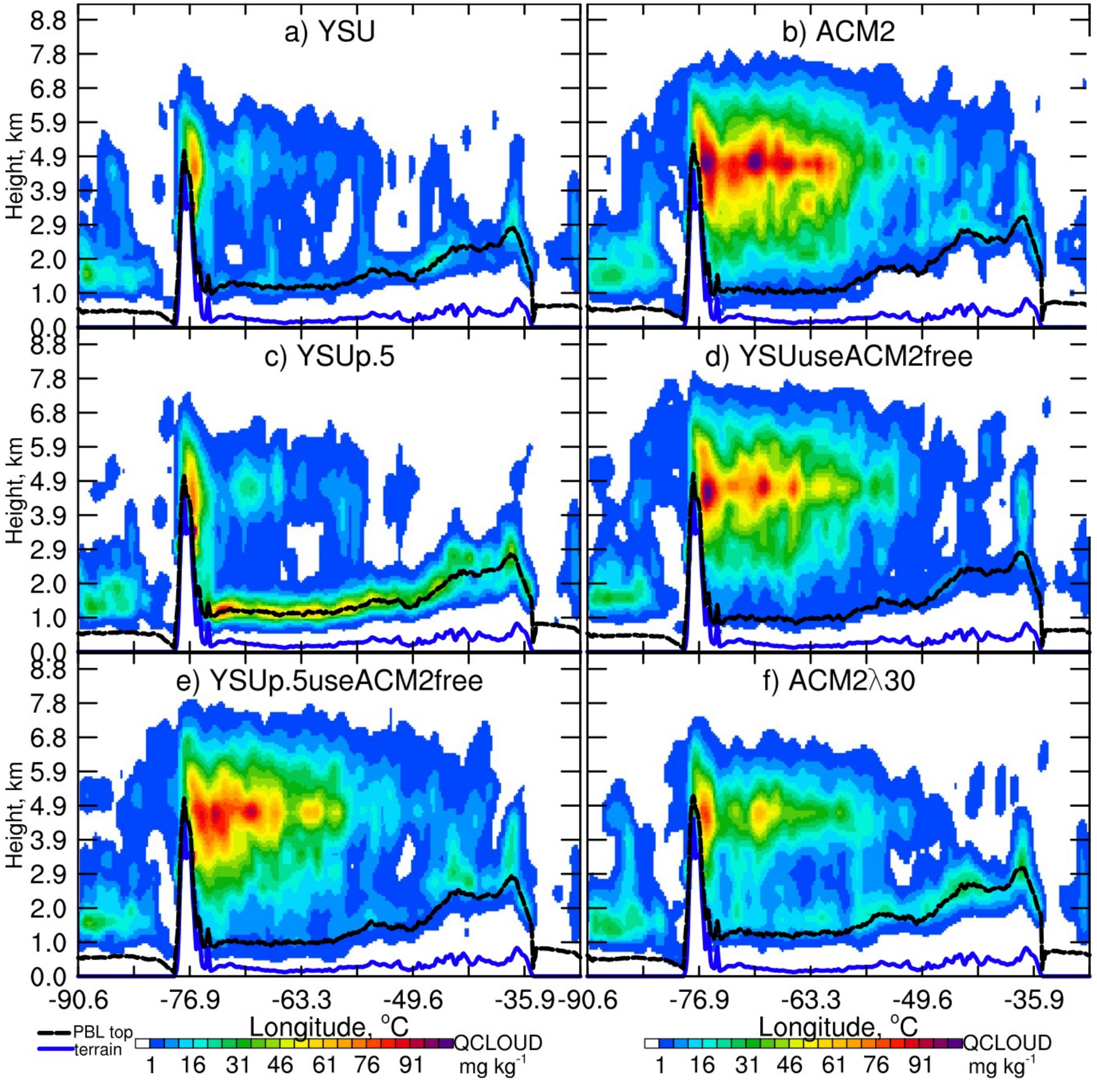
Rain rate

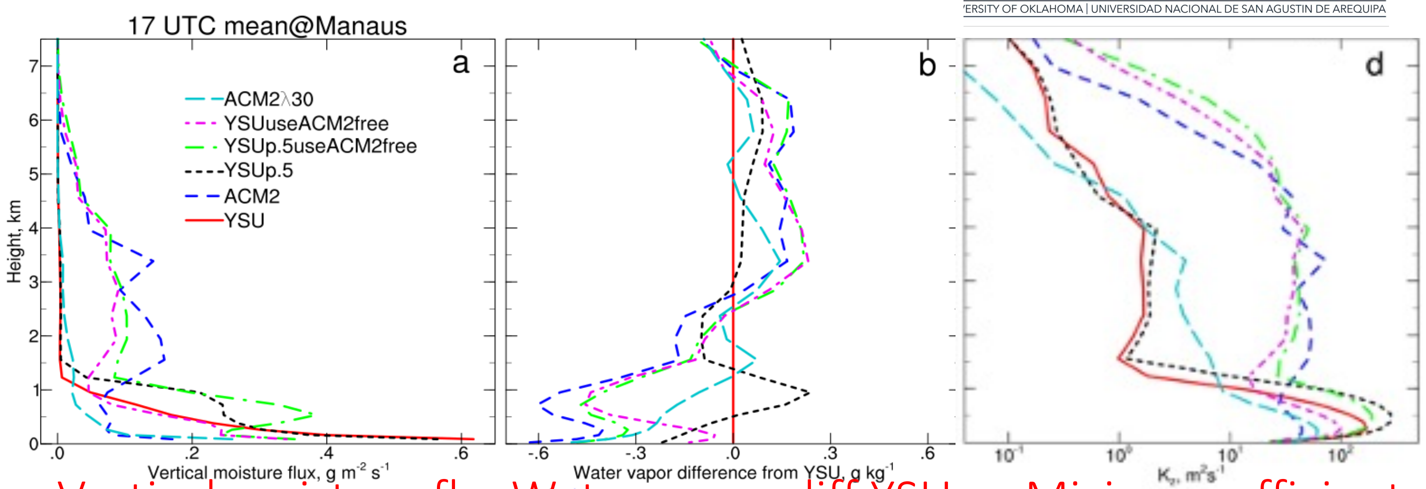


- ACM2 simulates more clouds, which reduces the solar heating reaching the ground.
- With less heating, convective instability is reduced.
- Therefore, less precipitation is produced.
- Such complex interactions are now scientific findings.

Hu, X.-M., Y. Huang, M. Xue, E. Martin, Y. Hong, M. Chen, H. M. Novoa, et al., Effects of lower troposphere vertical mixing on simulated clouds and precipitation over Amazon during the wet season. *J. Geophys. Res.-Atmospheres*, 10.1029/2023JD038553 .

Cloud sensitivity to different mixing treatments





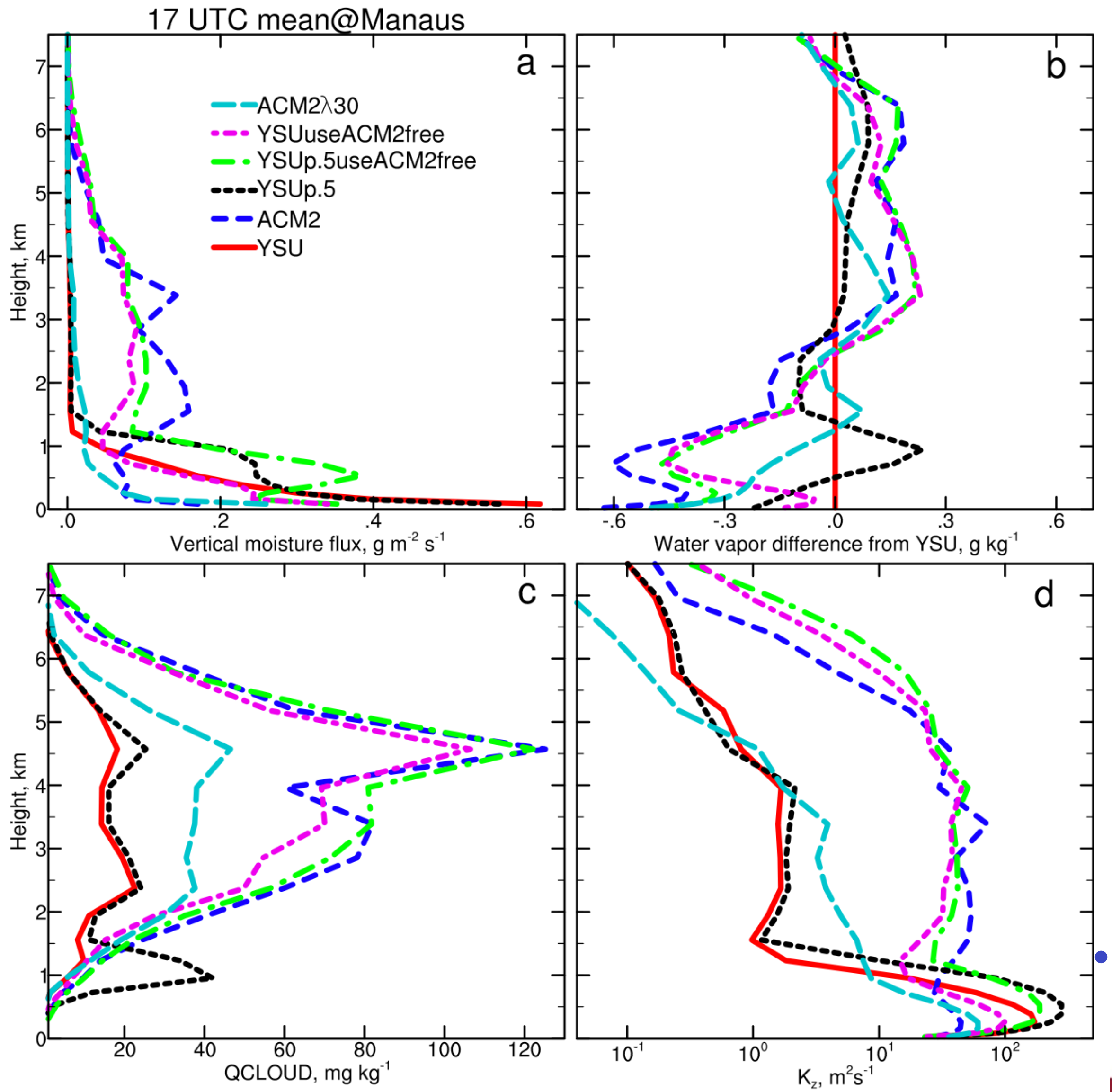
Vertical moisture flux Water vapor diff YSU Mixing coefficient

Table 1

Model Configuration for Sensitivity Simulations Modifying Parameters and Treatments in the Yonsei University (YSU) and Asymmetric Convective Model v2 (ACM2) Planetary Boundary Layer (PBL) Schemes

PBL	Grid spacings (km)	Experiment name	Changed parameters/treatments
YSU	15	YSU	$p = 2$ (default)
		YSUp.5	$p = 0.5$
		YSUuseACM2free	Use free troposphere treatment from ACM2
		YSUp.5useACM2free	$p = 0.5$ & use free troposphere treatment from ACM2
	3	3kmYSU	$p = 2$ (default)
		3kmYSUp.5	$p = 0.5$
		3kmYSUp.5useACM2free	$p = 0.5$ & use free troposphere treatment from ACM2
ACM2	15	ACM2	$\lambda = 80$ (default)
		ACM2λ30	$\lambda = 30$
	3	3kmACM2	$\lambda = 80$ (default)

Mixing in presence of clouds



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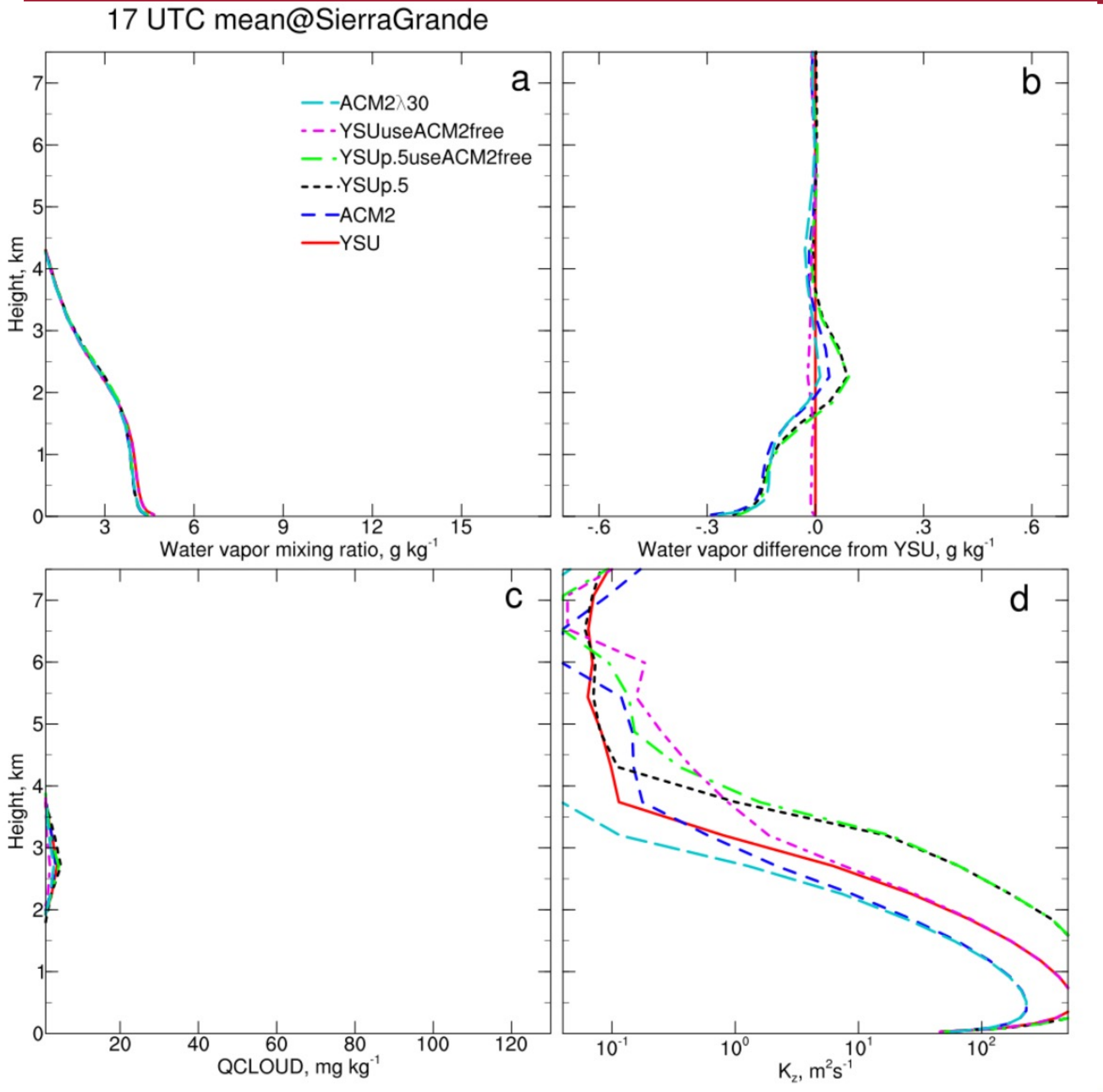
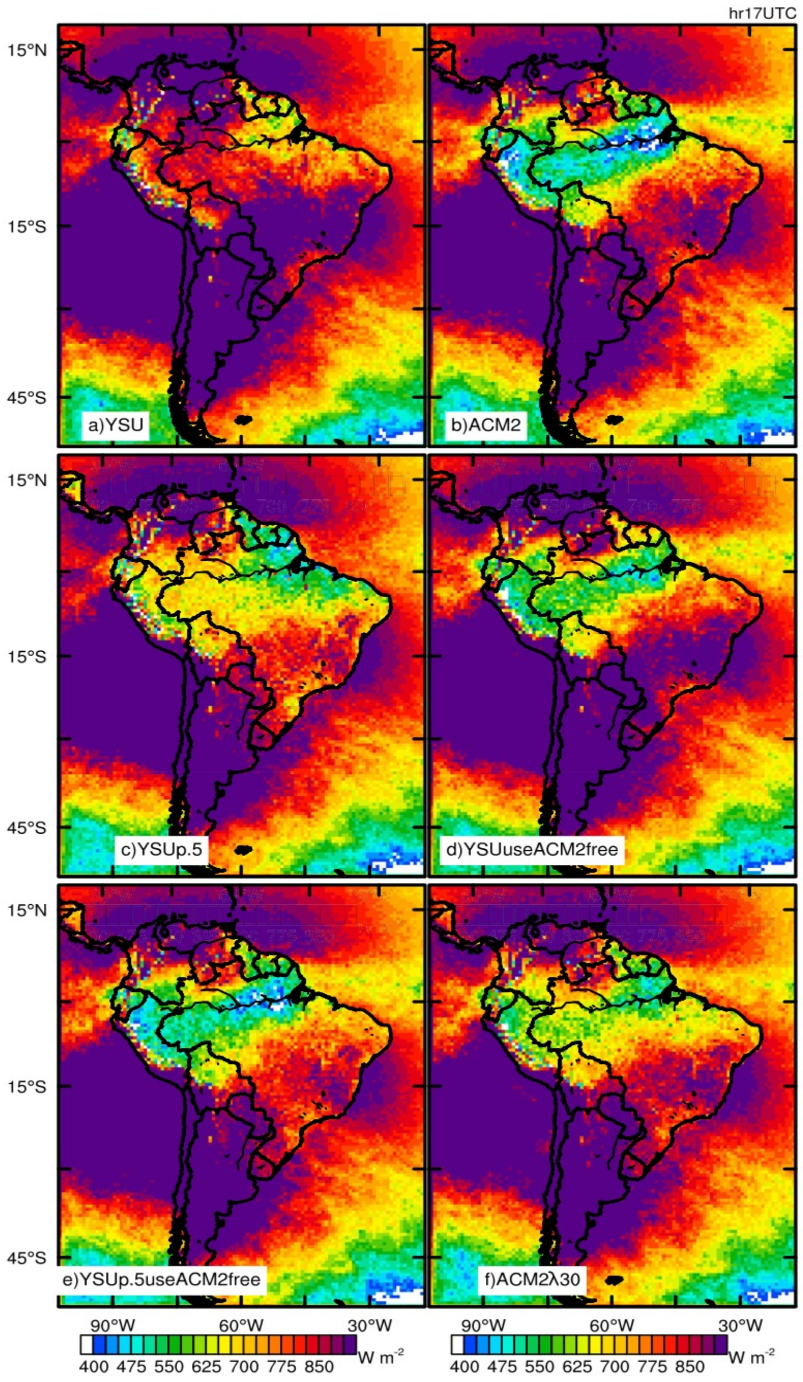
		YSUp.5useACM2free	$p = 0.5$ & use free troposphere treatment from ACM2
	3	3kmYSU	$p = 2$ (default)
		3kmYSUp.5	$p = 0.5$
		3kmYSUp.5useACM2free	$p = 0.5$ & use free troposphere treatment from ACM2
ACM2	15	ACM2	$\lambda = 80$ (default)
		ACM2λ30	$\lambda = 30$
	3	3kmACM2	$\lambda = 80$ (default)

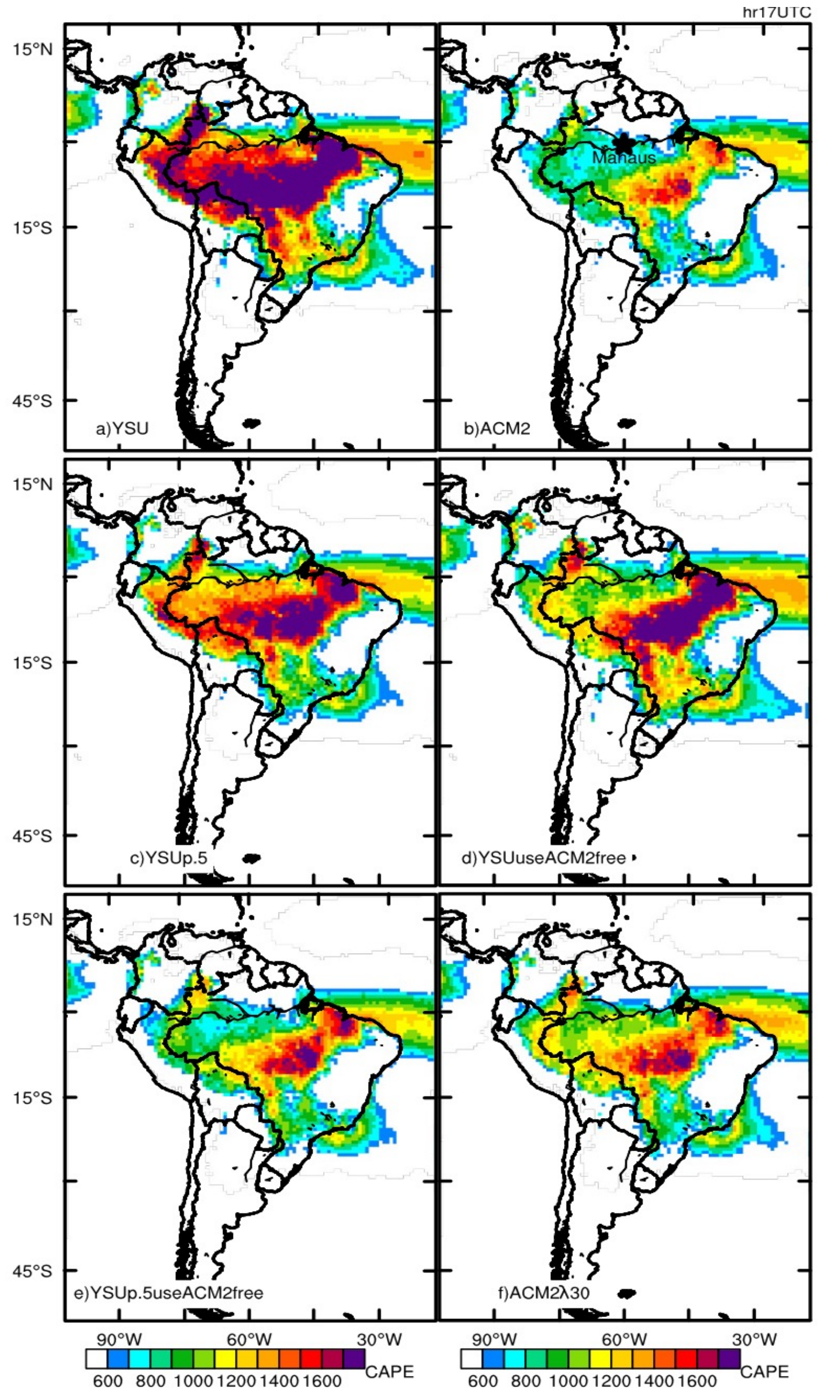
- ACM2 stronger FT vertical mixing in presence of **clouds**

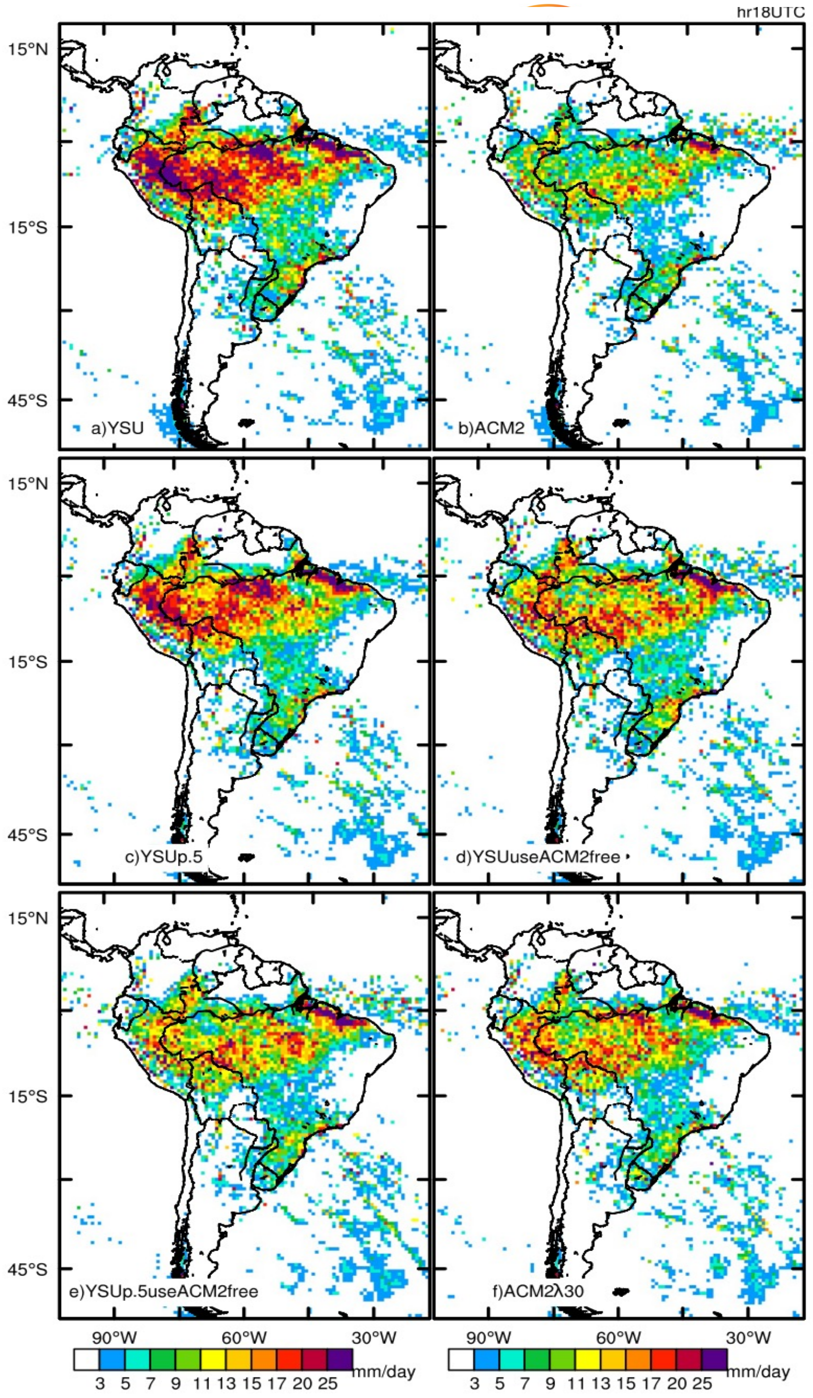
Mixing without clouds



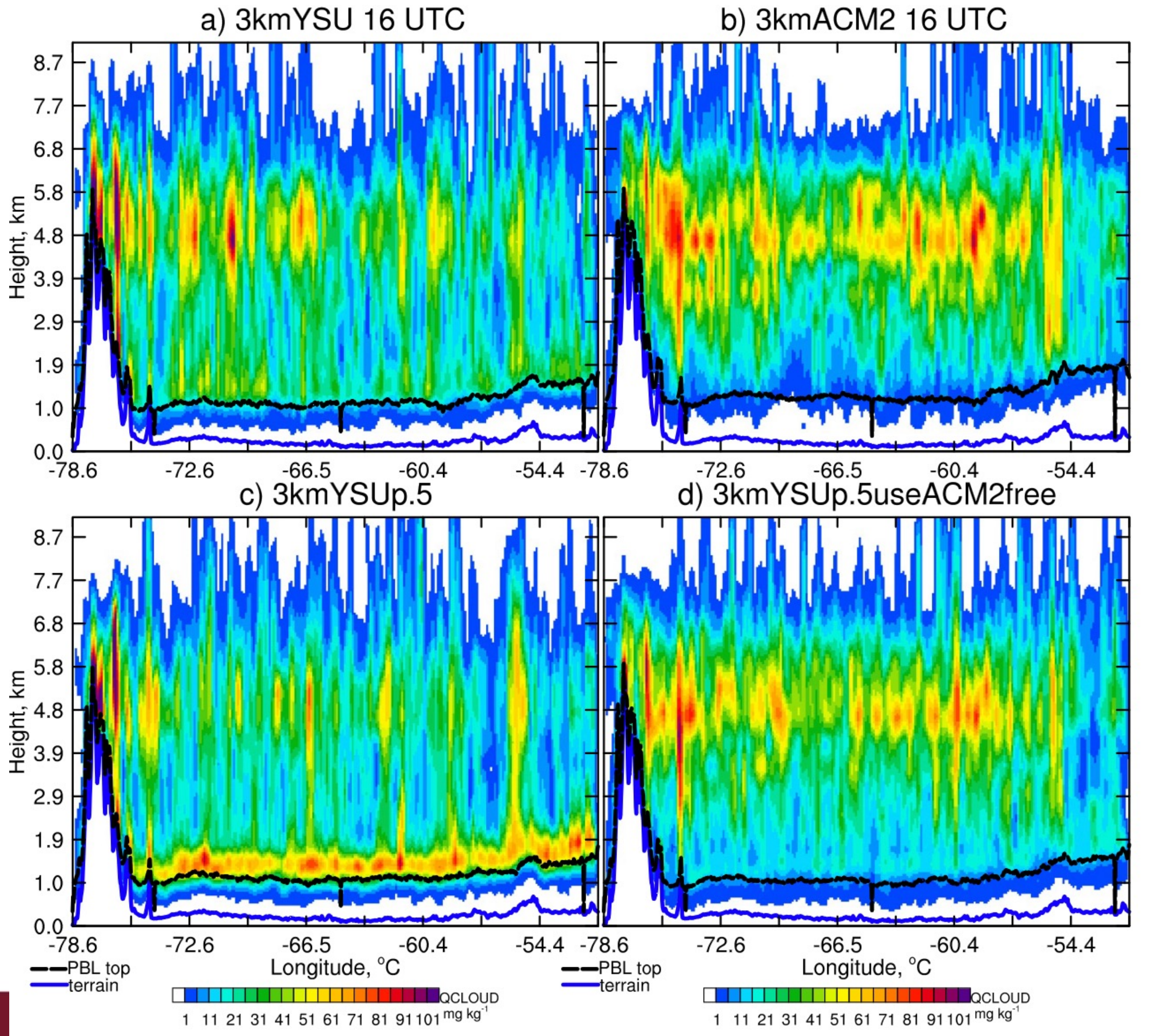
- ACM2 stronger FT vertical mixing in presence of **clouds**
- **Weak FT vertical mixing without clouds, which is not sensitive to PBL schemes**


hr17UTC
15°N
15°S
45°S
a)YSU
b)ACM2
c)YSUp.5
d)YSUuseACM2free
e)YSUp.5useACM2free
f)ACM2λ30
90°W 60°W 30°W
400 475 550 625 700 775 850
W m-2


hr17UTC
15°N
15°S
45°S
a)YSU
b)ACM2
Manaus
c)YSUp.5
d)YSUuseACM2free
e)YSUp.5useACM2free
f)ACM2λ30
90°W 60°W 30°W
600 800 1000 1200 1400 1600
CAPE


hr18UTC
15°N
15°S
45°S
a)YSU
b)ACM2
c)YSUp.5
d)YSUuseACM2free
e)YSUp.5useACM2free
f)ACM2λ30
90°W 60°W 30°W
3 5 7 9 11 13 15 17 20 25
mm/day

Clouds in the 3km simulations



- Similar sensitivity in 3km simulations

Precipitation in the 3km simulations

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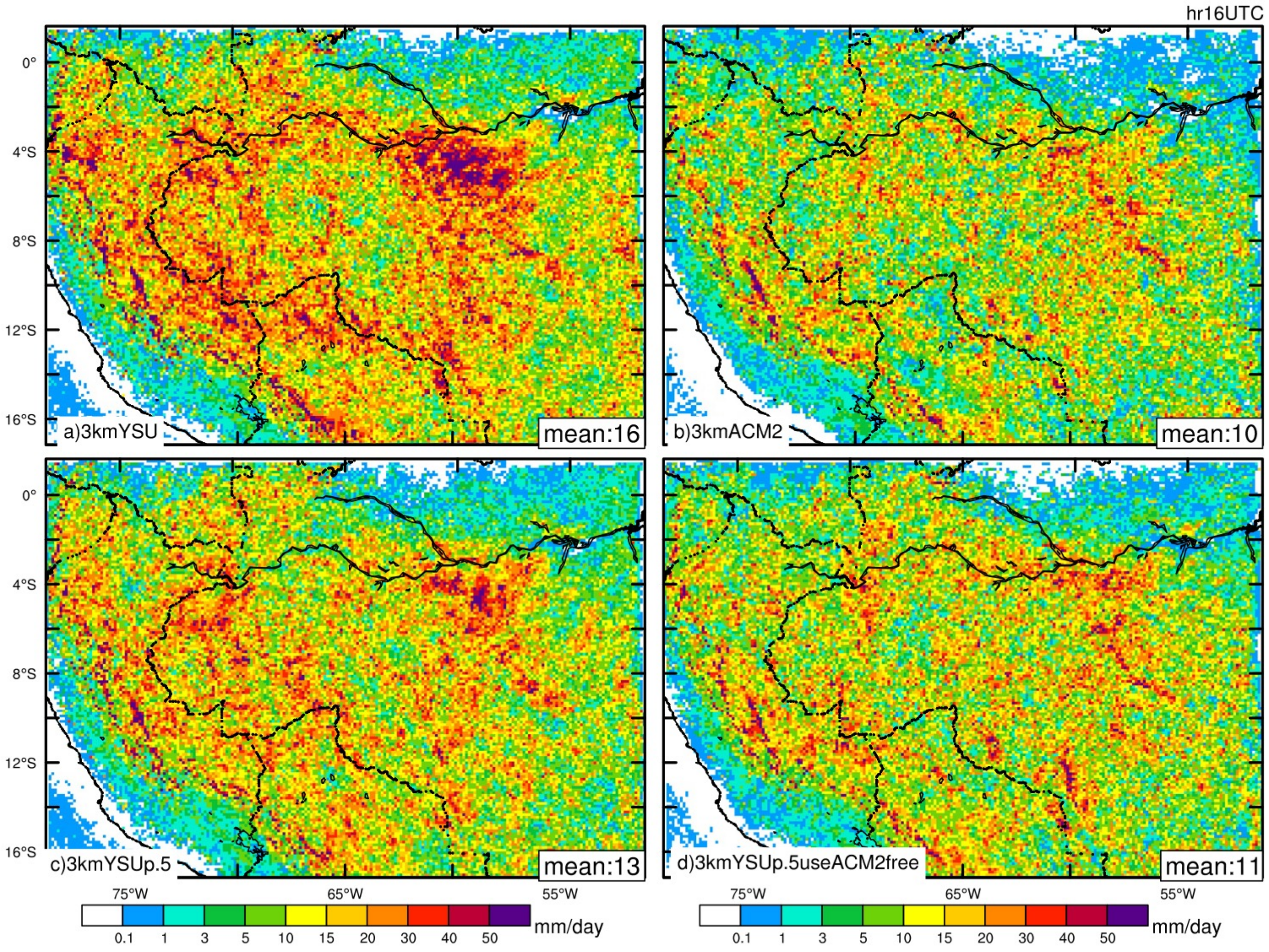
YSU

ACM2

YSU p0.5

YSU p0.5 use ACM2free



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Summary

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- Disentangle turbulence/cloud/precipitation processes over Amazon and reveal root cause for sensitivity to PBL schemes using WRF

- Free troposphere (FT) mixing becomes prominent in the presence of clouds, which in turn supports maintenance of the FT clouds that would otherwise dissipate

- Stronger vertical moisture relay transport in ACM2 PBL scheme supports thicker FT clouds, leading to reduced heating and precipitation

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JGR Atmospheres

RESEARCH ARTICLE
10.1029/2023JD038553

Key Points:

- Disentangle turbulence/cloud/precipitation processes over Amazon and reveal root cause for sensitivity to planetary boundary layer (PBL) schemes using the Weather Research and Forecasting model
- Free troposphere (FT) mixing becomes prominent in the presence of clouds, which in turn supports maintenance of the FT clouds that would otherwise dissipate
- Stronger vertical moisture relay transport in asymmetric convective model v2 (ACM2) PBL scheme supports thicker FT clouds, leading to reduced heating and precipitation

Effects of Lower Troposphere Vertical Mixing on Simulated Clouds and Precipitation Over the Amazon During the Wet Season

Xiao-Ming Hu[1,2], Yongjie Huang[1], Ming Xue[1,2], Elinor Martin[2], Yang Hong[3], Mengye Chen[3], Hector Mayol Novoa[4], Renee McPherson[5], Andres Perez[4], Isaac Yanqui Morales[4], and Auria Julieta Flores Luna[4]

[1]Center for Analysis and Prediction of Storms, University of Oklahoma, Norman, OK, USA, [2]School of Meteorology, University of Oklahoma, Norman, OK, USA, [3]School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK, USA, [4]Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru, [5]Department of Geography and Environmental Sustainability, University of Oklahoma, Norman, OK, USA

Abstract Planetary boundary layer (PBL) schemes parameterize unresolved turbulent mixing within the PBL and free troposphere (FT). Previous studies reported that precipitation simulation over the Amazon in South America is quite sensitive to PBL schemes and the exact relationship between the turbulent mixing

Hu, X.-M., Y. Huang, M. Xue, E. Martin, Y. Hong, M. Chen, H. M. Novoa, et al., Effects of lower troposphere vertical mixing on simulated clouds and precipitation over Amazon during the wet season. *J. Geophys. Res.-Atmospheres*, 10.1029/2023JD038553 .

Part II: air quality

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The impact of **turbulence**, and **dynamic processes** on **air quality** over South America

Severe air pollution issues over Peru

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Fig. 2 Relationship between particulate matter and meteorological parameters that presented significant correlation in the atmosphere of the region of Arequipa, Peru, during 2018

Larrea Valdivia et al., 2020

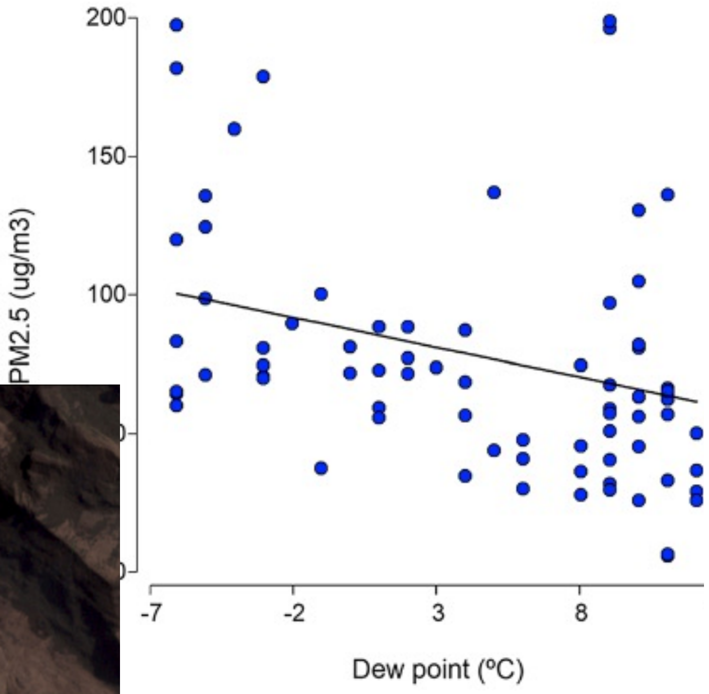

Table 0.1. Recommended AQG levels and interim targets

Pollutant	Averaging time	Interim target 1	Interim target 2	Interim target 3	Interim target 4	AQG level
$PM_{2.5}$, µg/m³	Annual	35	25	15	10	5
	24-hour[a]	75	50	37.5	25	15
PM_{10}, µg/m³	Annual	70	50	30	20	15
	24-hour[a]	150	100	75	50	45
O_3, µg/m³	Peak season[b]	100	70	–	–	60
	8-hour[a]	160	120	–	–	100

Air pollution level exceeded the WHO air quality guidance level by an order of magnitude.

Primary pollutants over Peru: aerosols, mercury, O_3.

Sources: vehicles, mining, wildfires.

Severe SO_2 pollution over Peru

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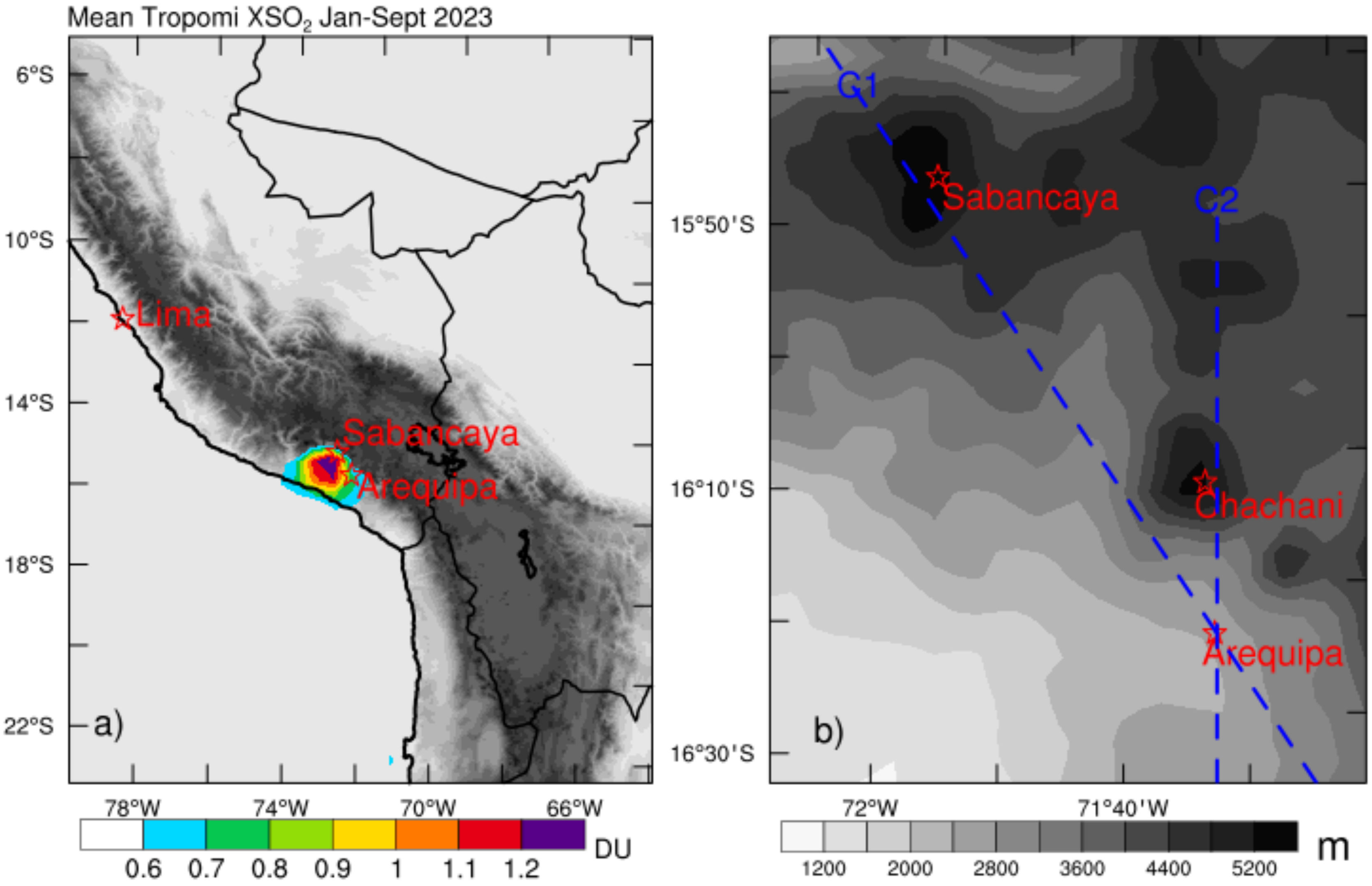


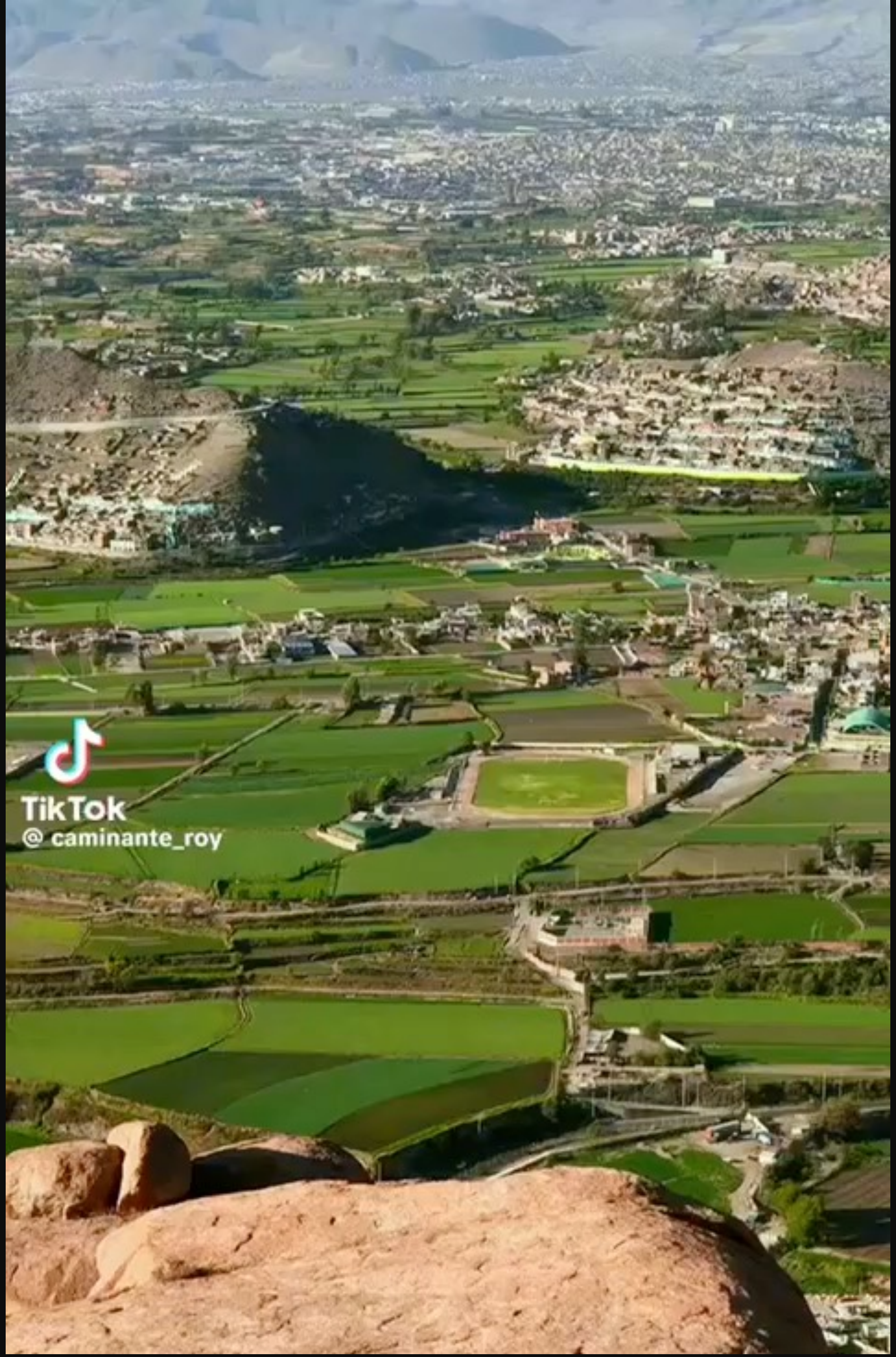
Worst SO_2 pollution over Arequipa

Sources: volcanos

How does Arequipa look like?

Beautiful city beside mountains

video



Air pollution simulations using WRF/Chem

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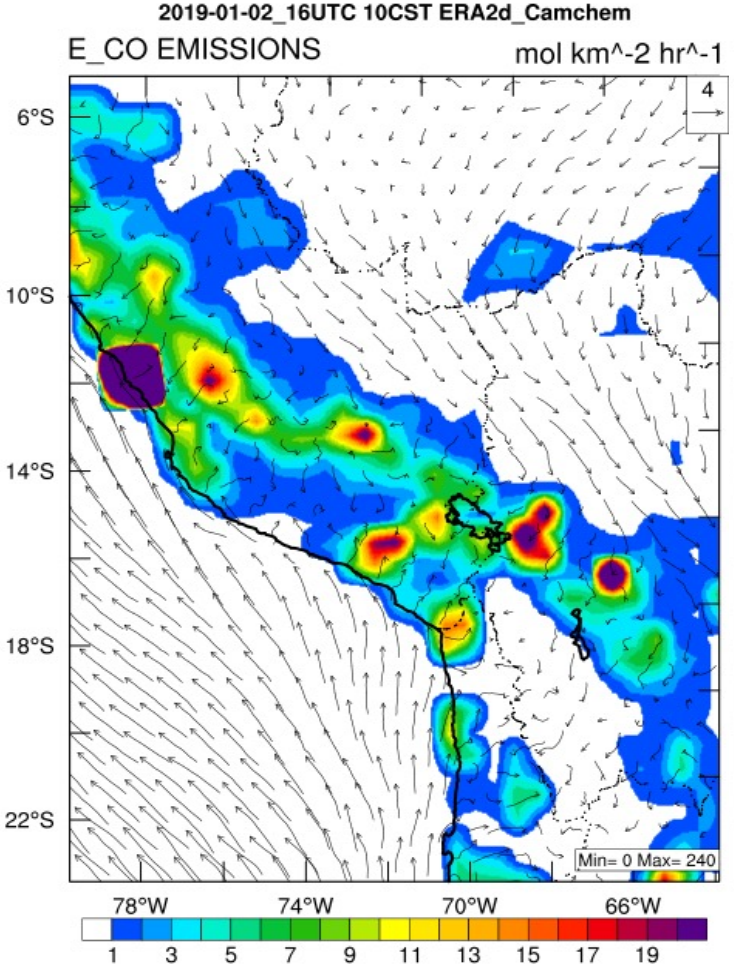
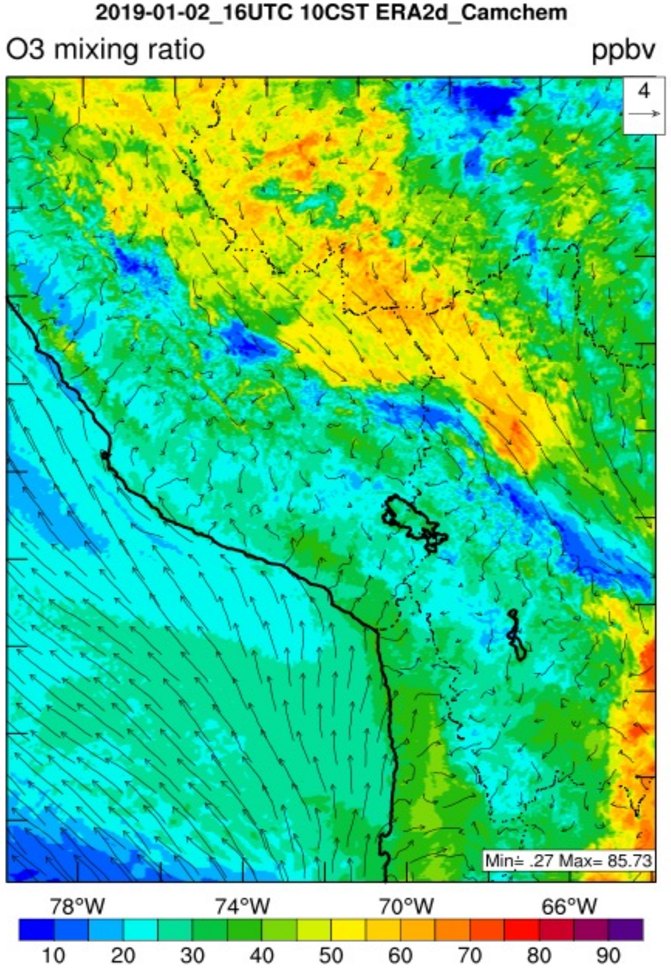
CO emissions



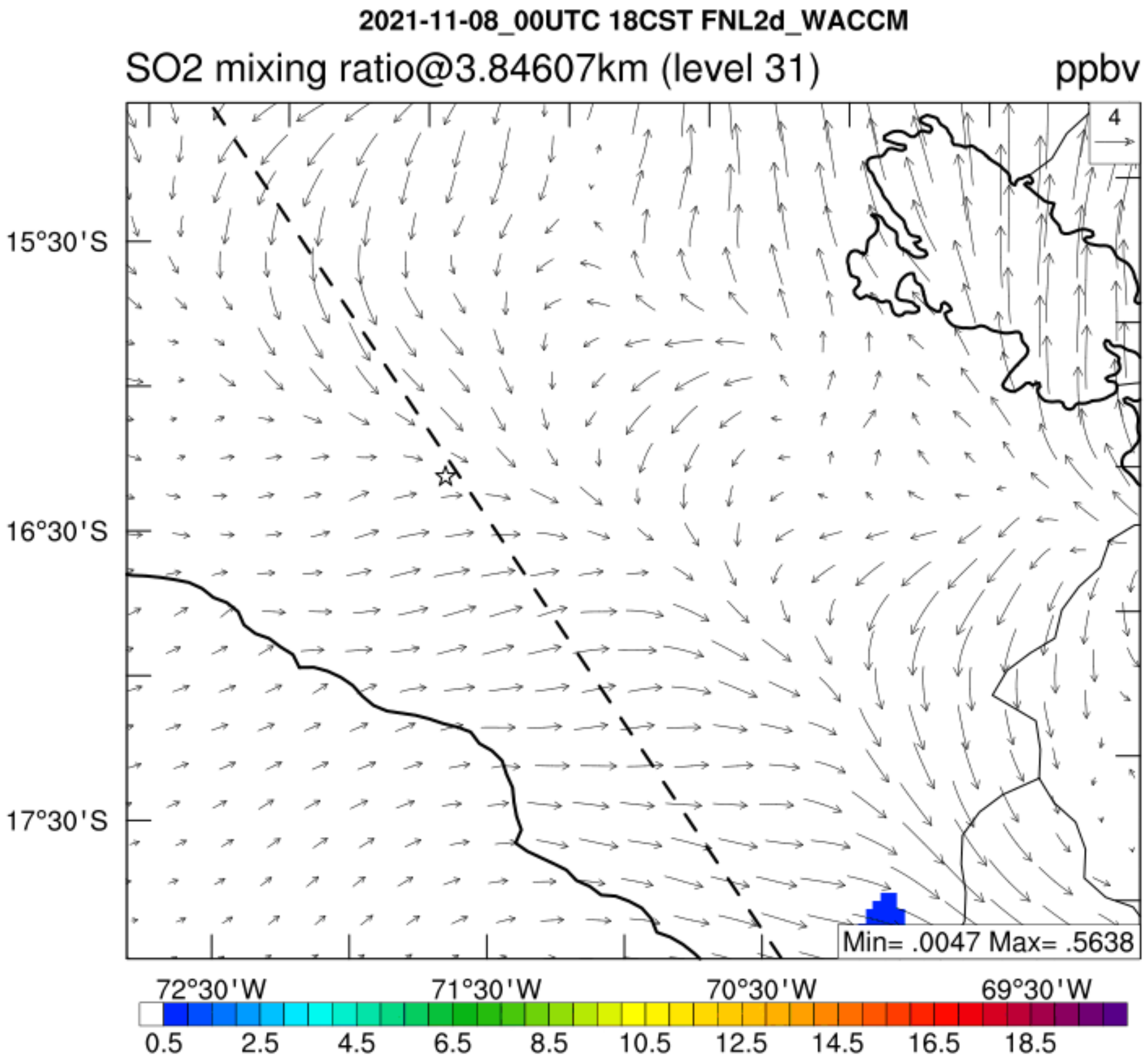
O3 mixing ratios



WRF/Chem
air quality simulation/forecasting system
set up over Peru:
https://caps.ou.edu/micronet/Peru.html

Grid spacing: 15km (south America) => **3km (Peru)**
Grid points: 690 × 540 (d02)
Emissions: 0.5° × 0.5° RETRO (REanalysis of the TROpospheric chemical composition)
Efficiency: 2day forecast in 1 day using 4 skx nodes
Chemical IC/BC: CAM-Chem

Air pollution forecasts, adding Volcán Sabancaya



If movie not working on left, click https://caps.ou.edu/micronet/Brazil/Simulations/4.3.3/wrfchem4.3.3FNL025_2d_Peru_WACCMICBC_Sabancaya.2021110800/wrfout_d02_so2_zoomin_layer31_0.gif

Star marks Arequipa

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Volcano emissions may not affect ambient air quality

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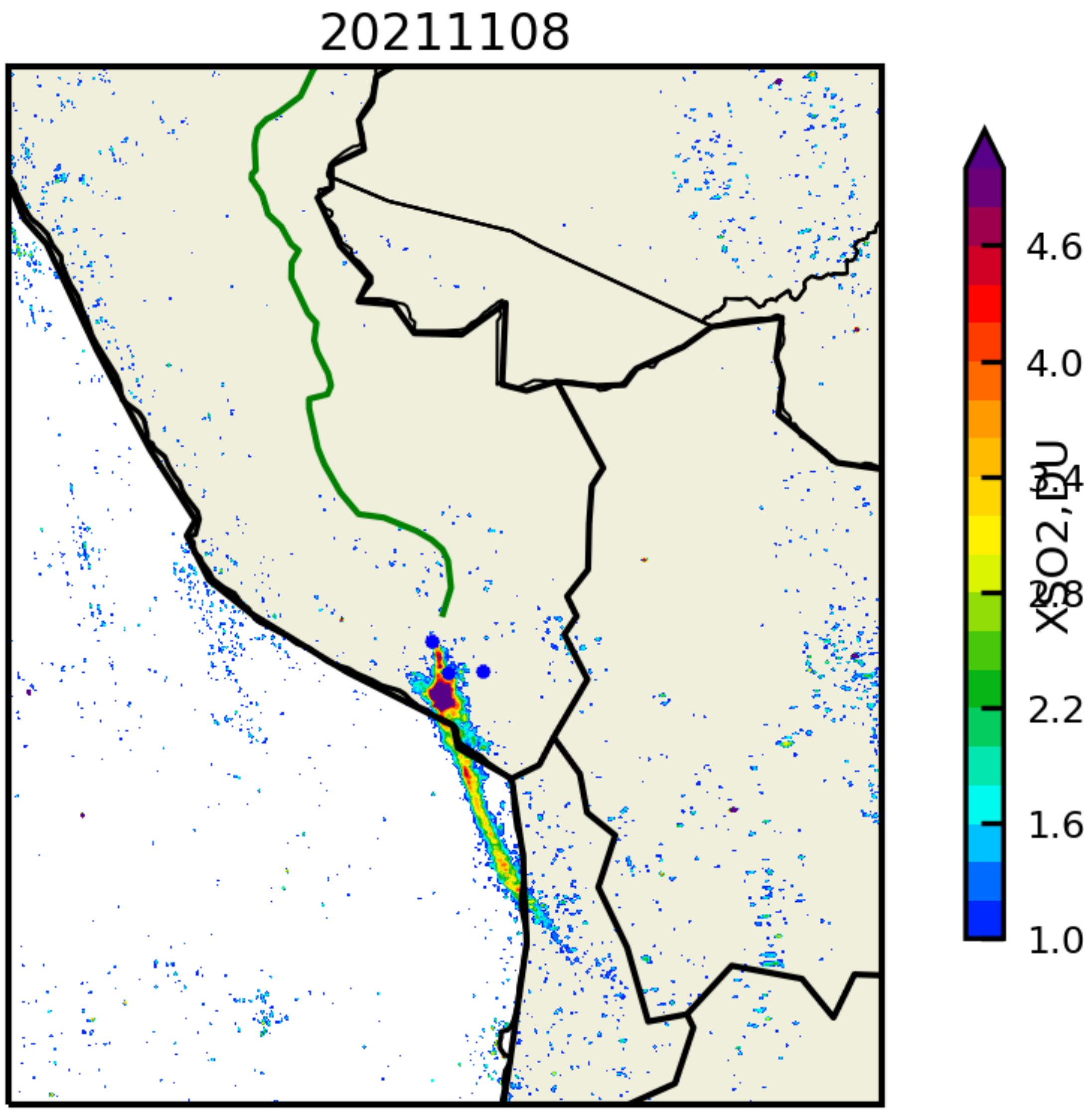
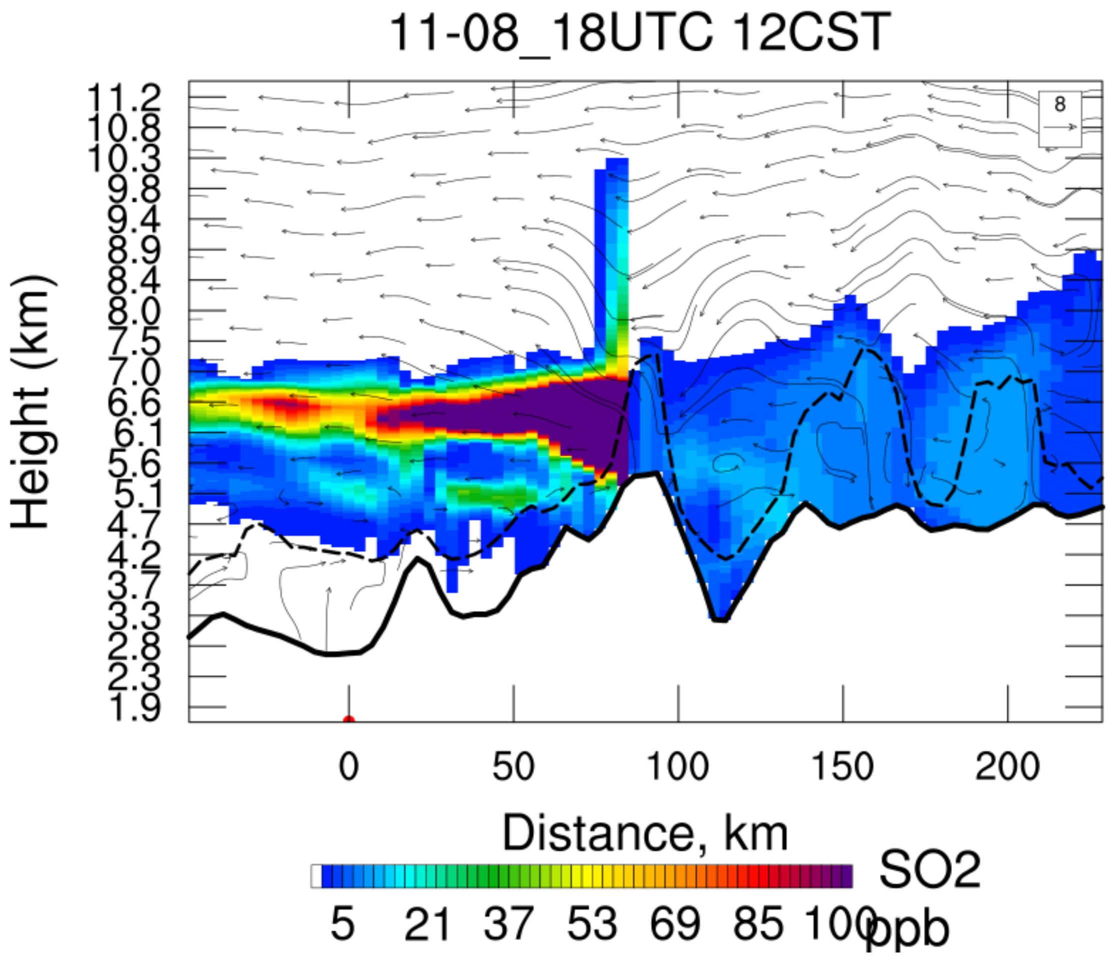
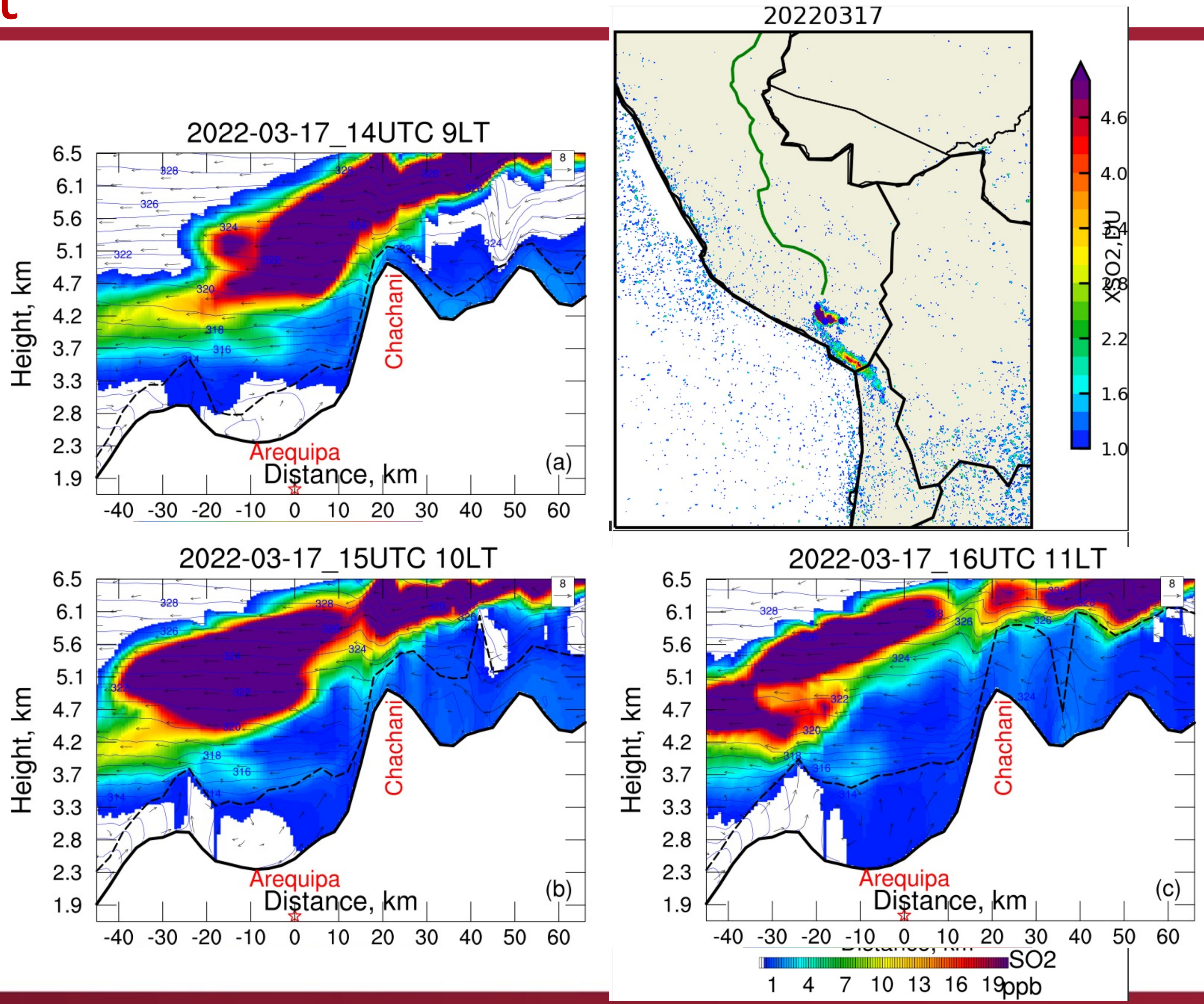




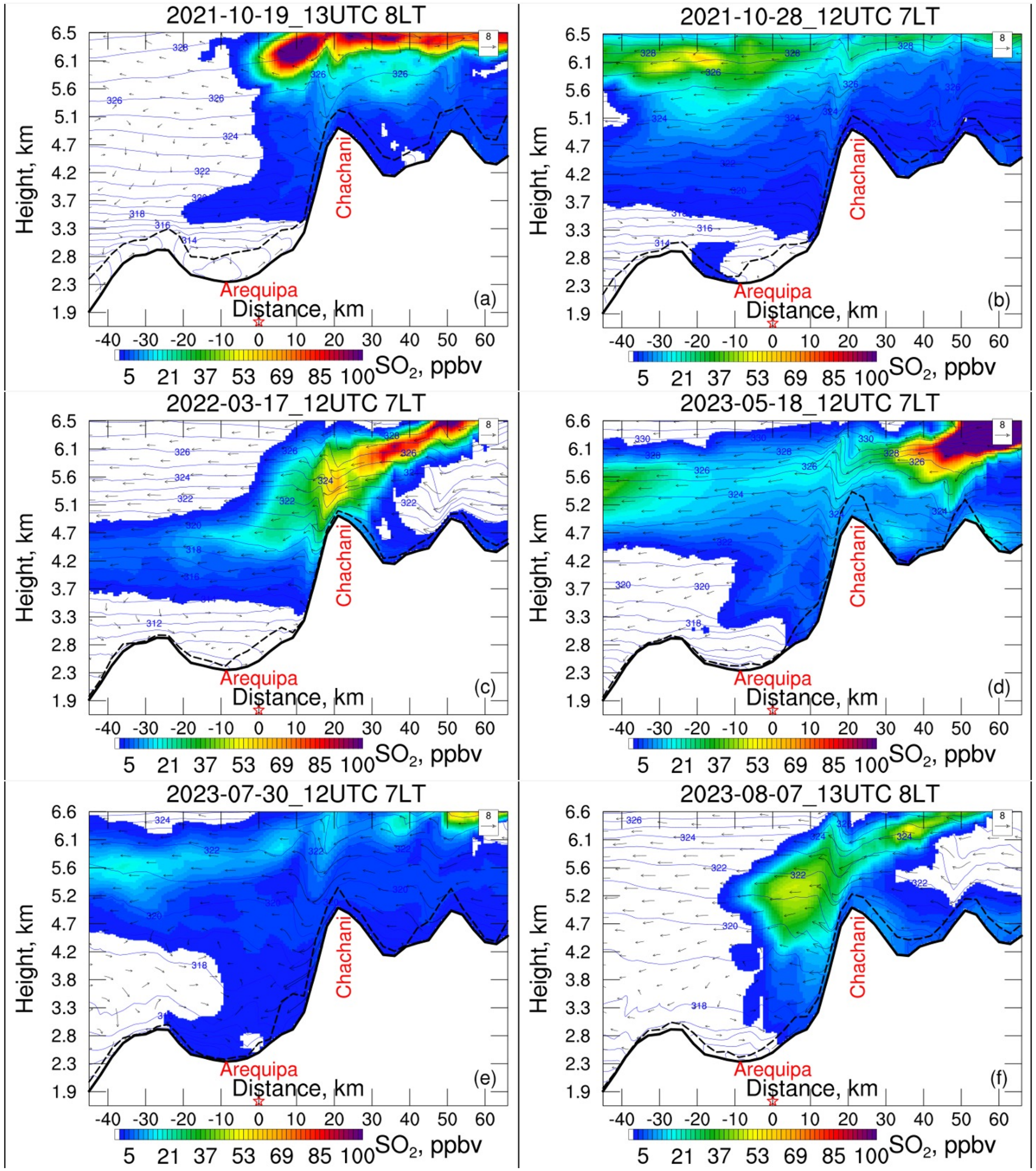
Volcano affects ambient air quality through mountain-mediated transport



Volcano plumes exacerbate pollution under certain conditions

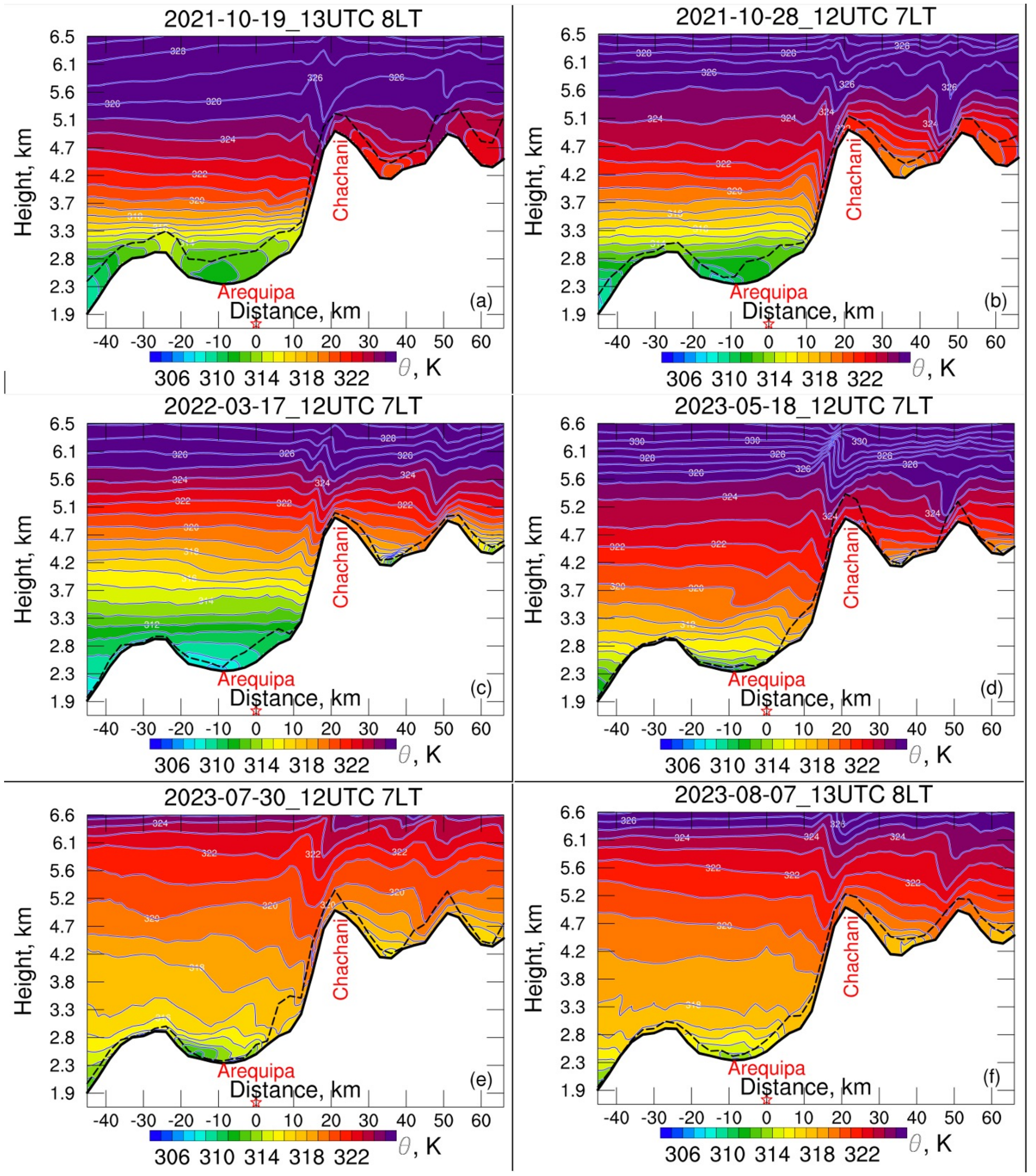
Nighttime downward transport of SO_2 plume, 6 cases

due to leeside gravity waves



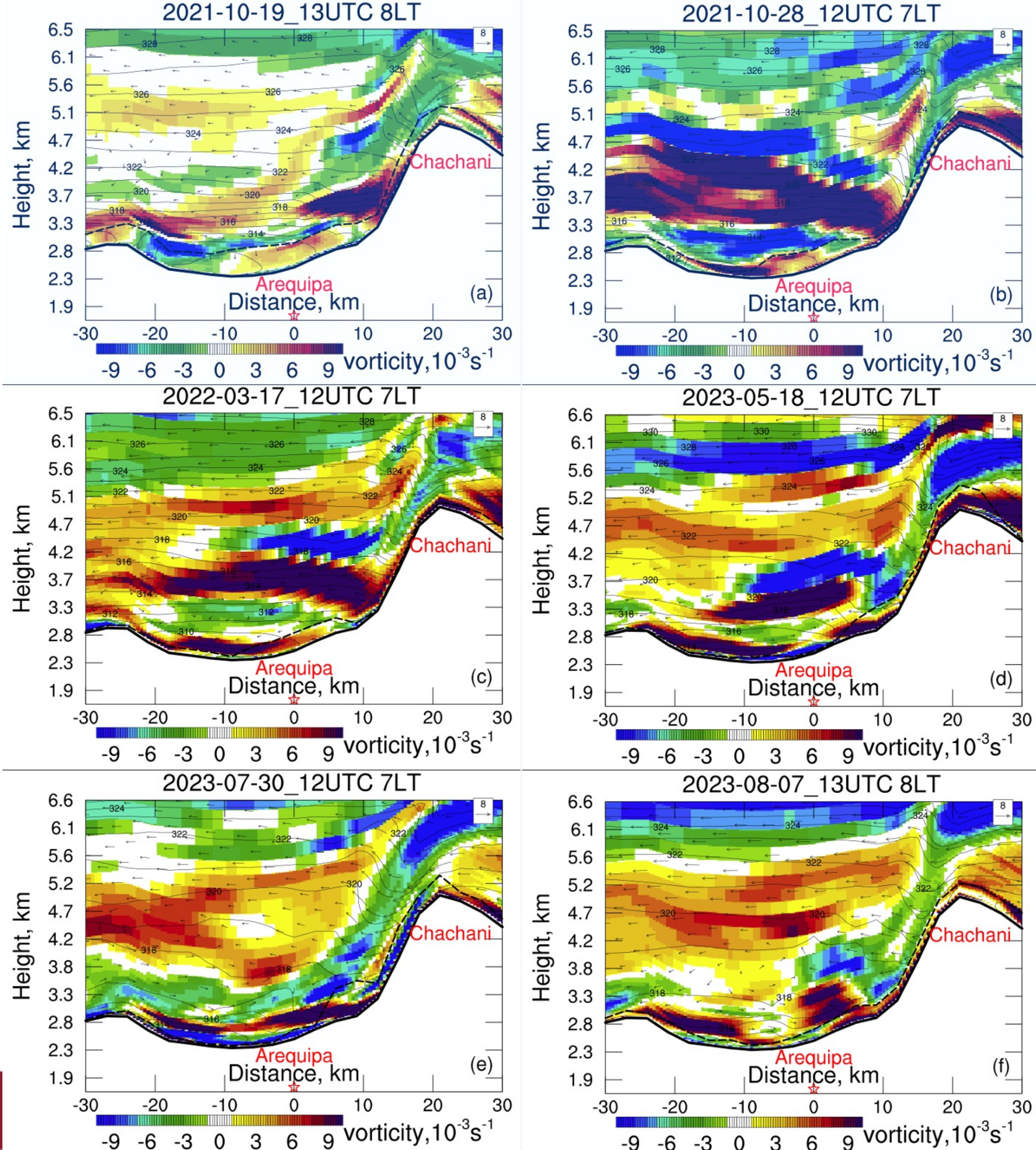
Potential temperature corss-section

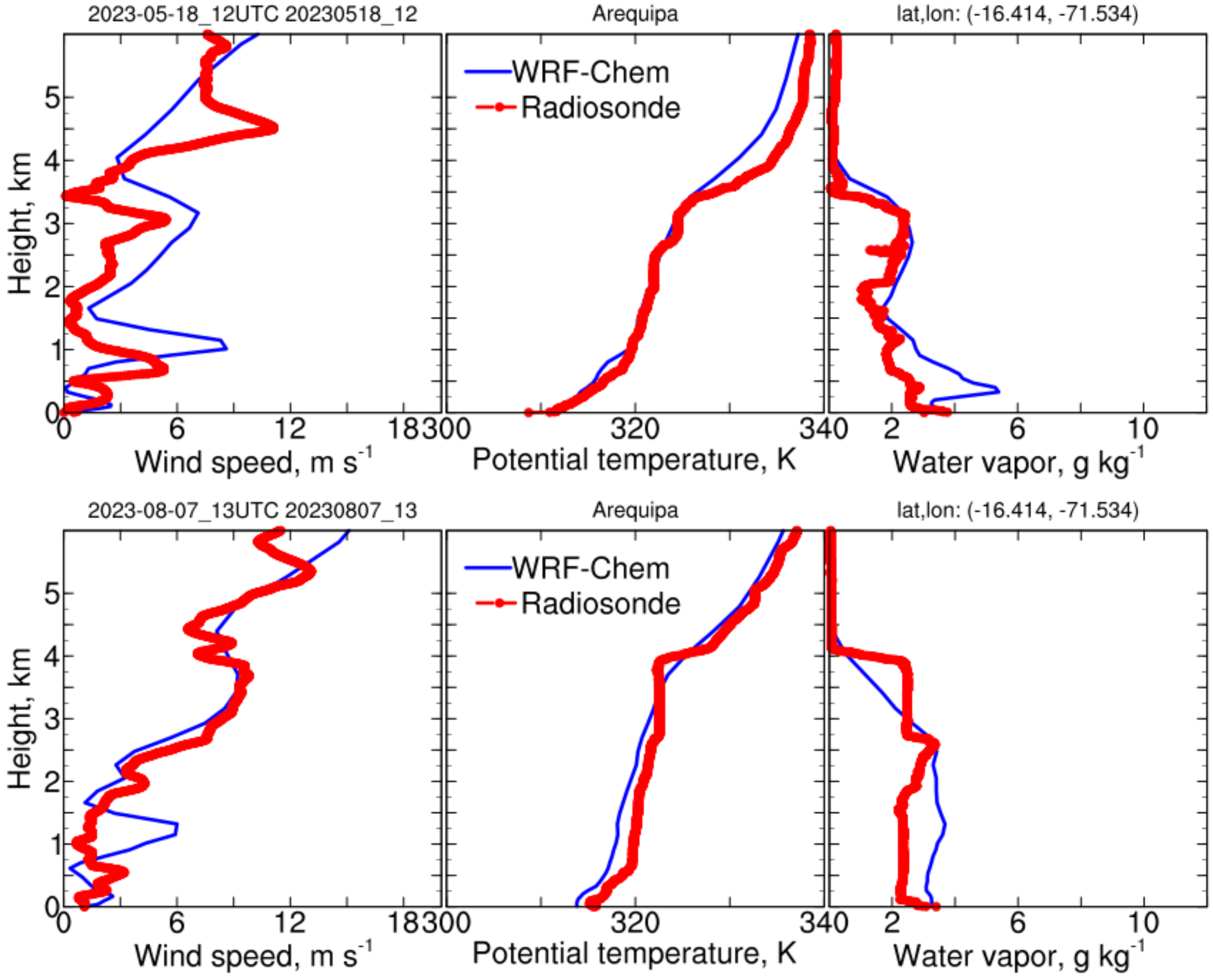
Nighttime gravity waves indicated by isentropes



Nighttime downward transport

Indicated by y-z plane-normal vorticity



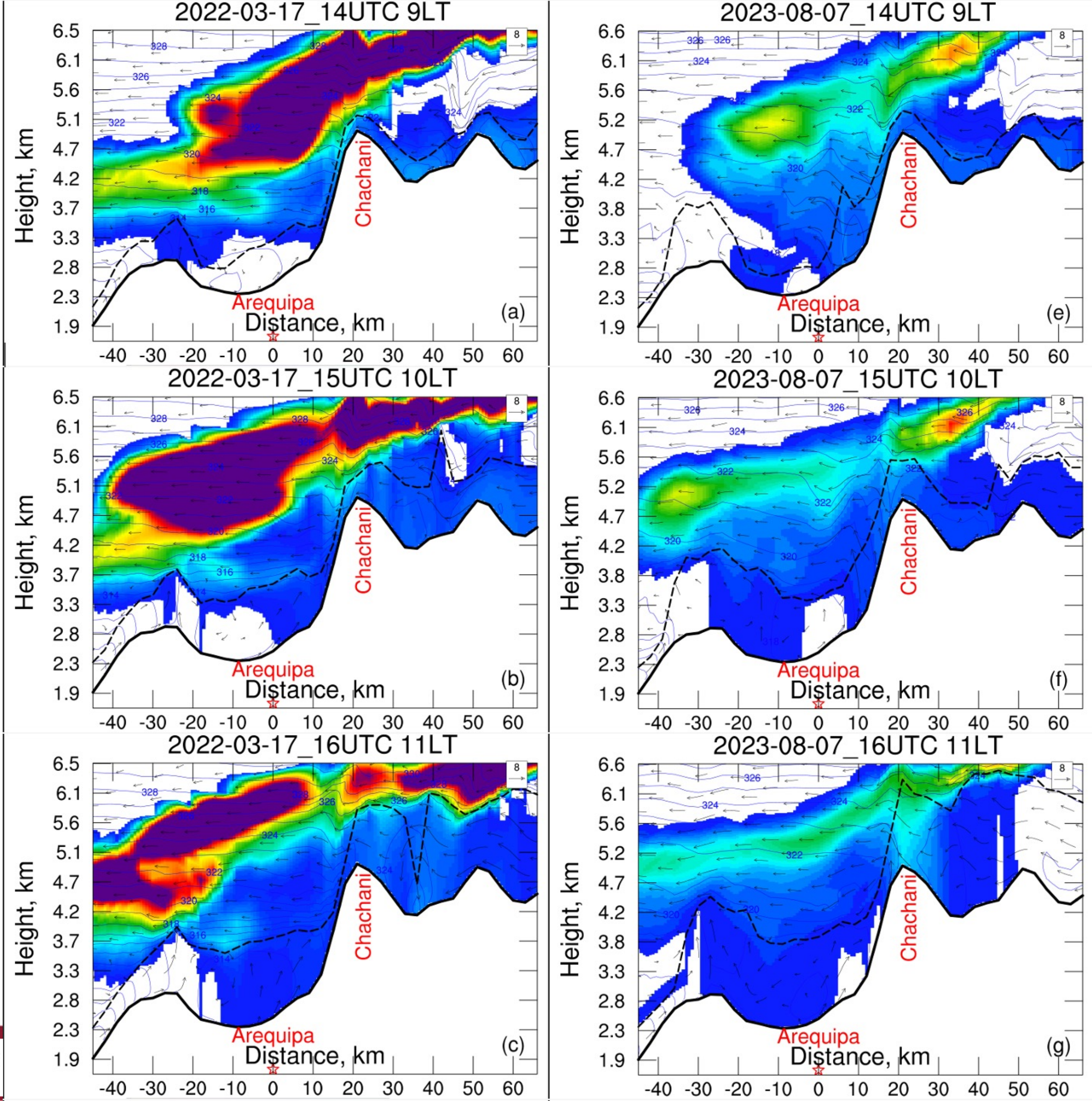


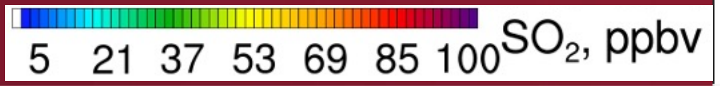
Early mornings (7-8 local time) soundings

Near surface stability may prevent the SO_2 plume to reach the surface

CH_4 plume transported to the surface during daytime

by convective boundary layer eddies





Dynamic processes isolated by idealized simulatioon

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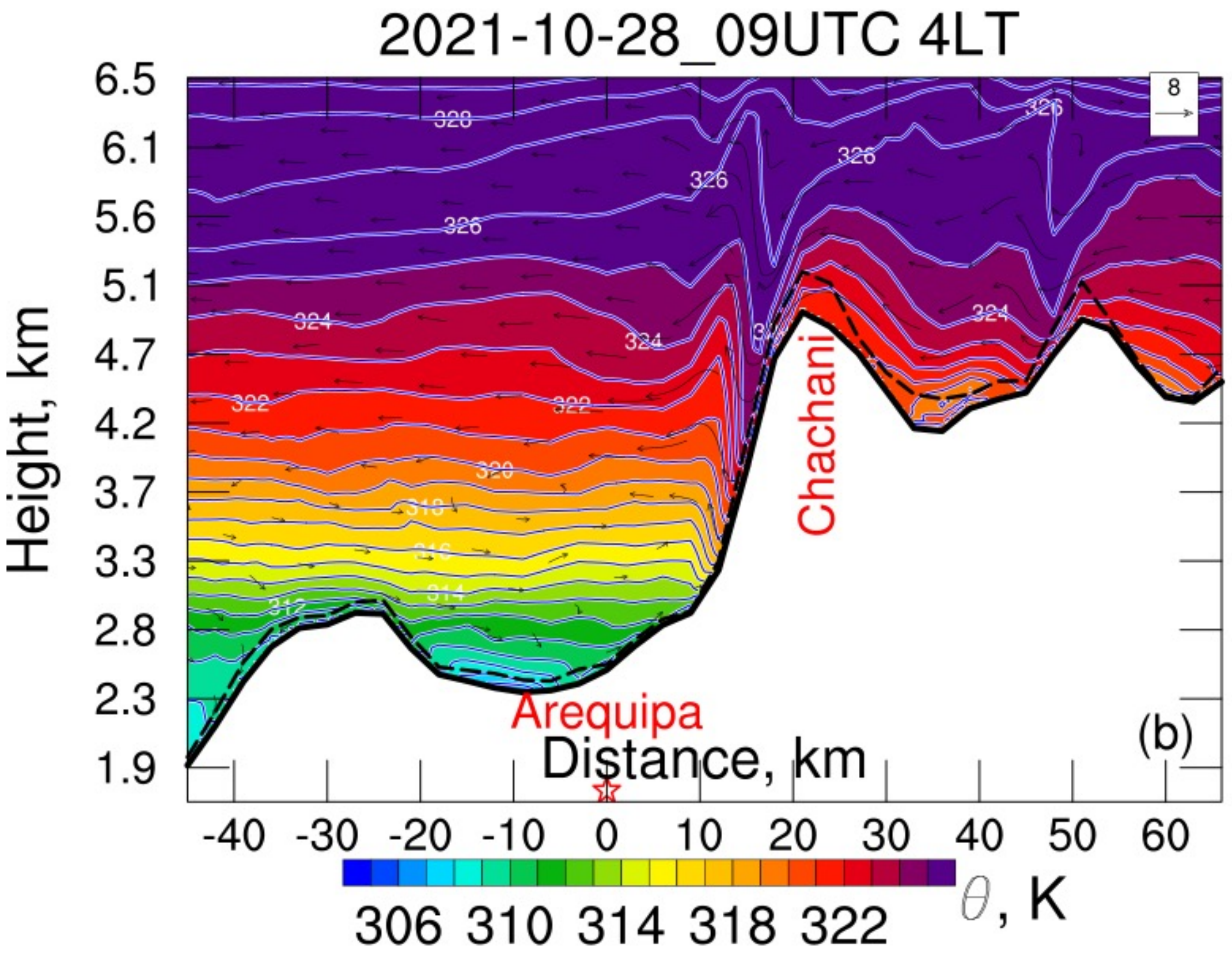
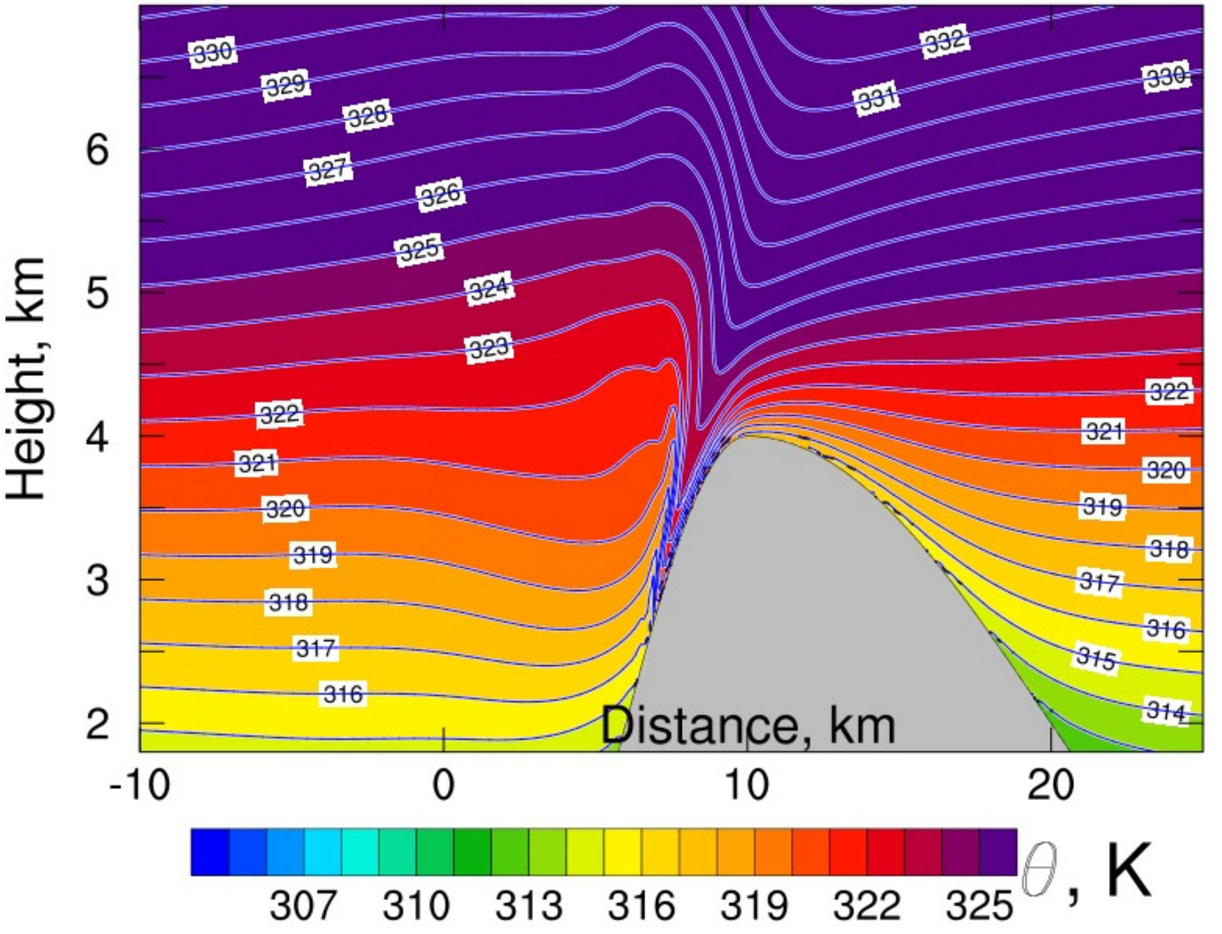


WRF/Chem



Idealized simulation with only dynamic effects

Part II Summary

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THE UNIVERSITY OF OKLAHOMA | UNIVERSIDAD NACIONAL DE SAN AGUSTIN DE AREQUIPA

1. Plumes from volcano Sabancaya can be transported to Arequipa through a series of advection and dispersion processes, thus exacerbating air pollution.
2. Sabancaya plumes can be captured by mountain Chachani and transported downward to Arequipa by nighttime downslope winds behind the gravity wave.
3. Daytime convective boundary layer entrainment and dispersion further brings elevated plume over Arequipa to the surface.