Summer rainfall over the southwestern Tibetan Plateau controlled by deep convection over the Indian subcontinent

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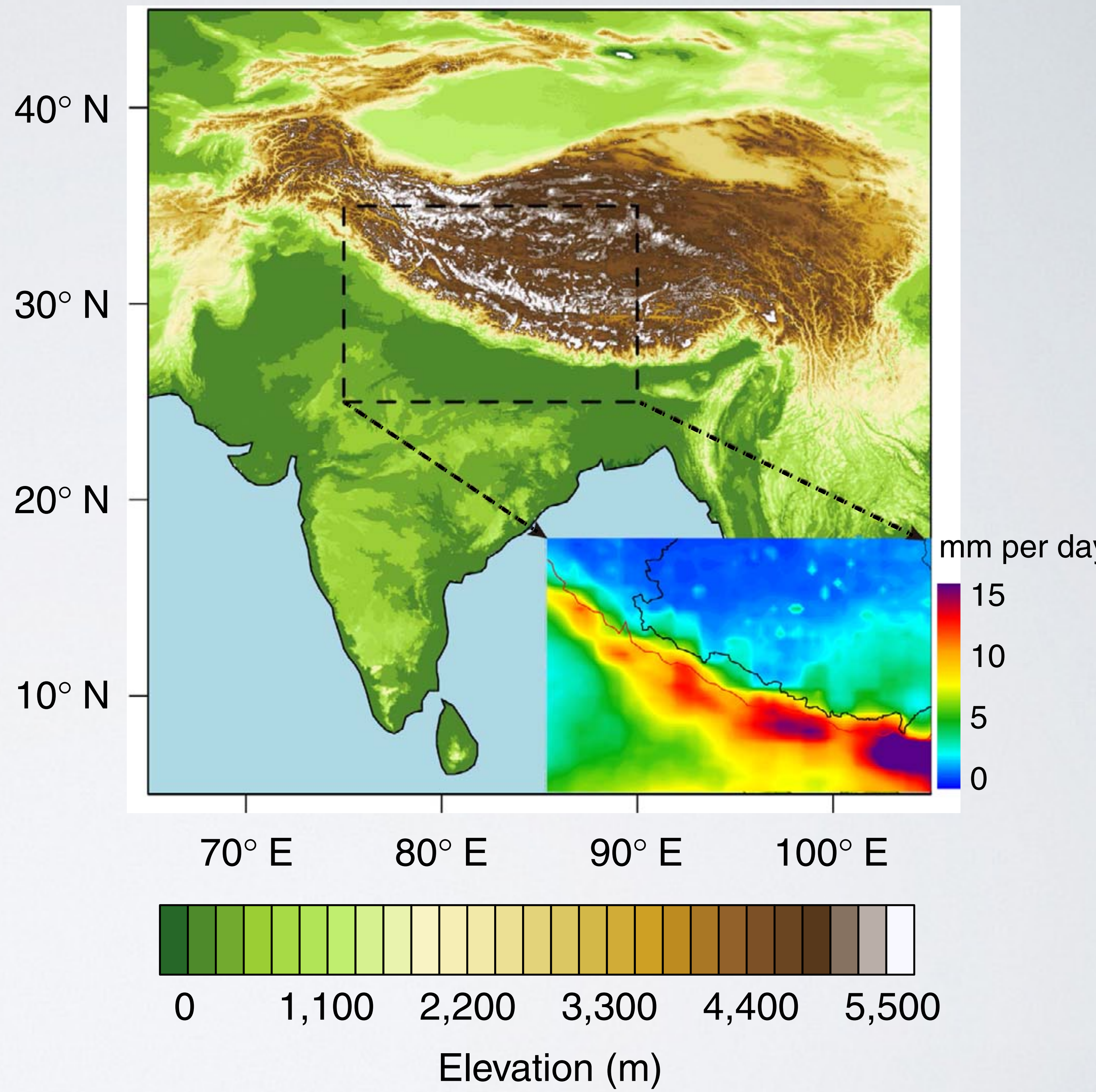
Dong et al., 2016 | doi:10.1038/ncomms10925

The southwestern Tibetan Plateau (SWTP)

- A semiarid region with a vulnerable ecosystem, drier and more isolated than the more extensively studied eastern Tibetan Plateau
- Sharp declines in glacier extent over recent decades
- Orographic precipitation dominates during summertime (JJAS), with the Himalayan foothills receiving much more rainfall than the SWTP
- Precipitation events over the SWTP often serve as precursors for storm systems downstream, with some systems that develop over the SWTP later causing extreme rainfall and severe flooding in East Asia



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Key question:
What controls summer precipitation over the SWTP?

- Identifying these mechanisms is critical for understanding glacier mass balance, river runoff into surrounding regions, and threats to local ecosystems under climate change
- The Himalayas are more than 5000 m above sea level on average between 75–95°E, but the interior of the SWTP receives more precipitation than many regions blocked by high mountains (such as the desert regions of the southwestern US or South America)
- Upslope flow is the primary source of summer rainfall over the eastern Tibetan Plateau, but much of this arrives via the relatively deep and wide Brahmaputra corridor — can upslope flow still account for observed precipitation amounts in the southwest?
- Numerical simulations and isotopic analyses indicate that much of the rainfall can be traced back to the nearby ocean — by what route(s) does this moisture arrive?

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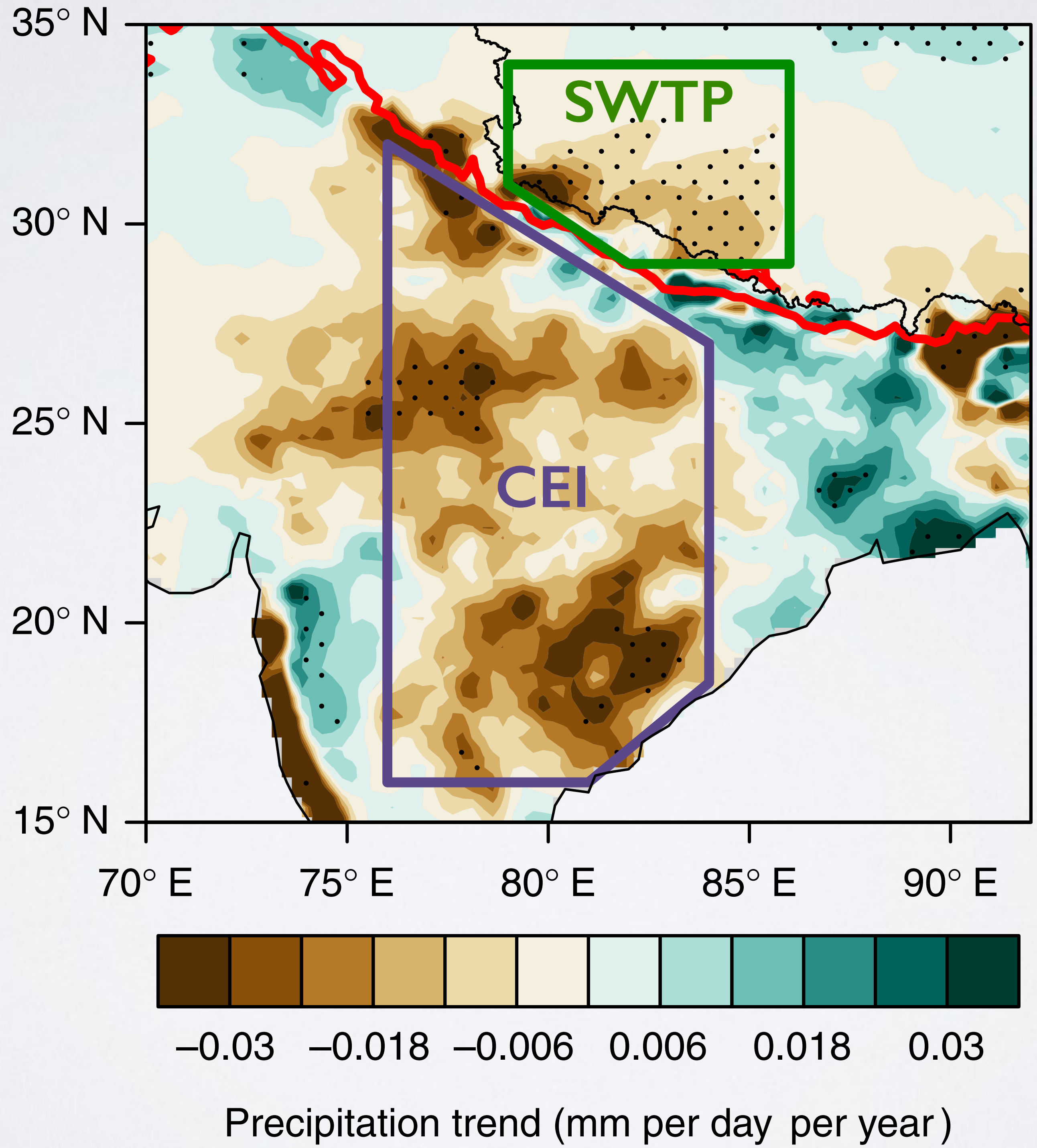
Precipitation trends:

Summertime rainfall has decreased over both the SWTP and central Eastern India (CEI).



Trends for 1951–2007 based on the APHRODITE precipitation analysis

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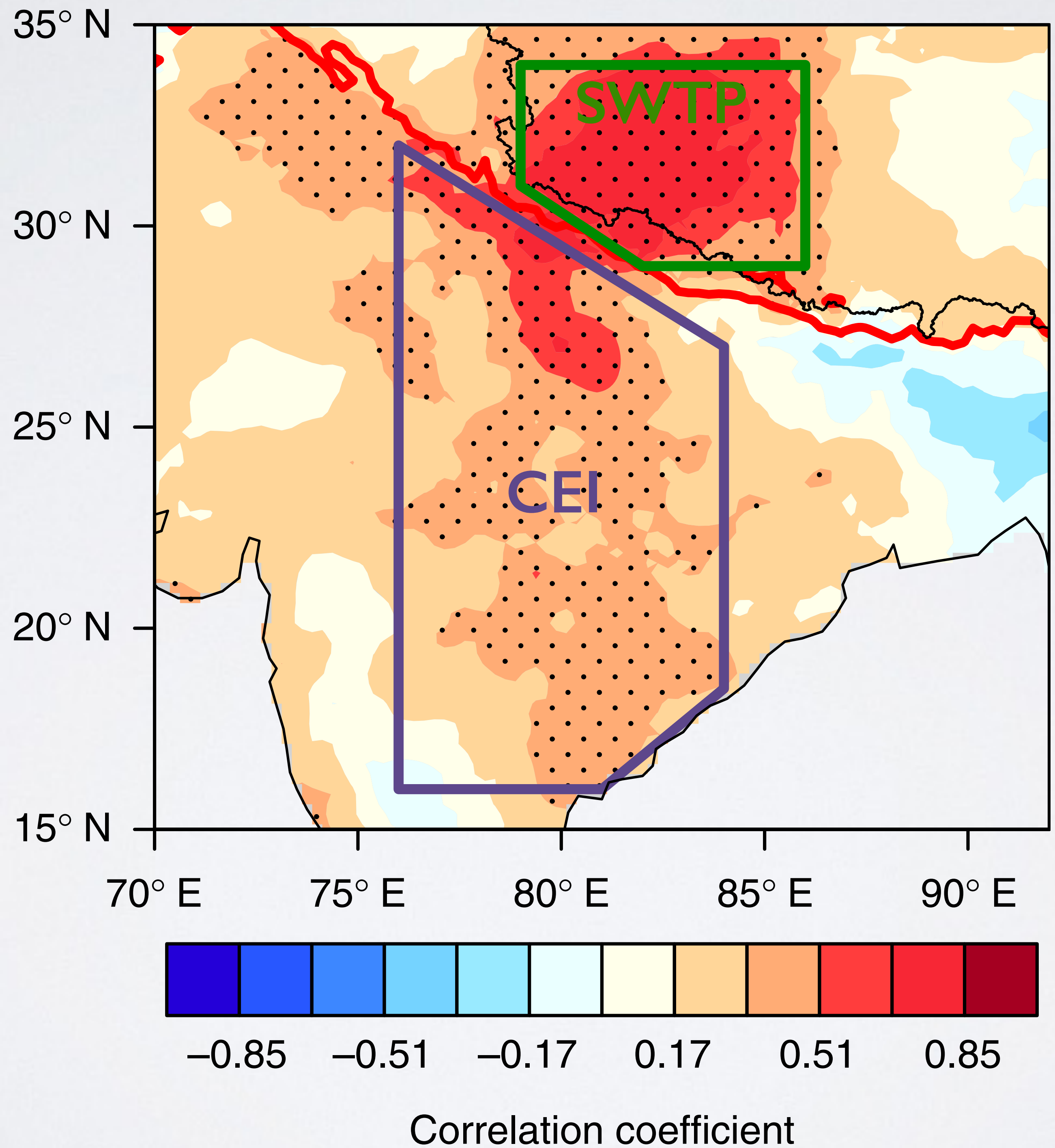
Spatial correlations:

Summertime rainfall over the SWTP is strongly correlated with rainfall over much of CEI at interannual time scales.



Correlations of summer precipitation with the SWTP area-mean

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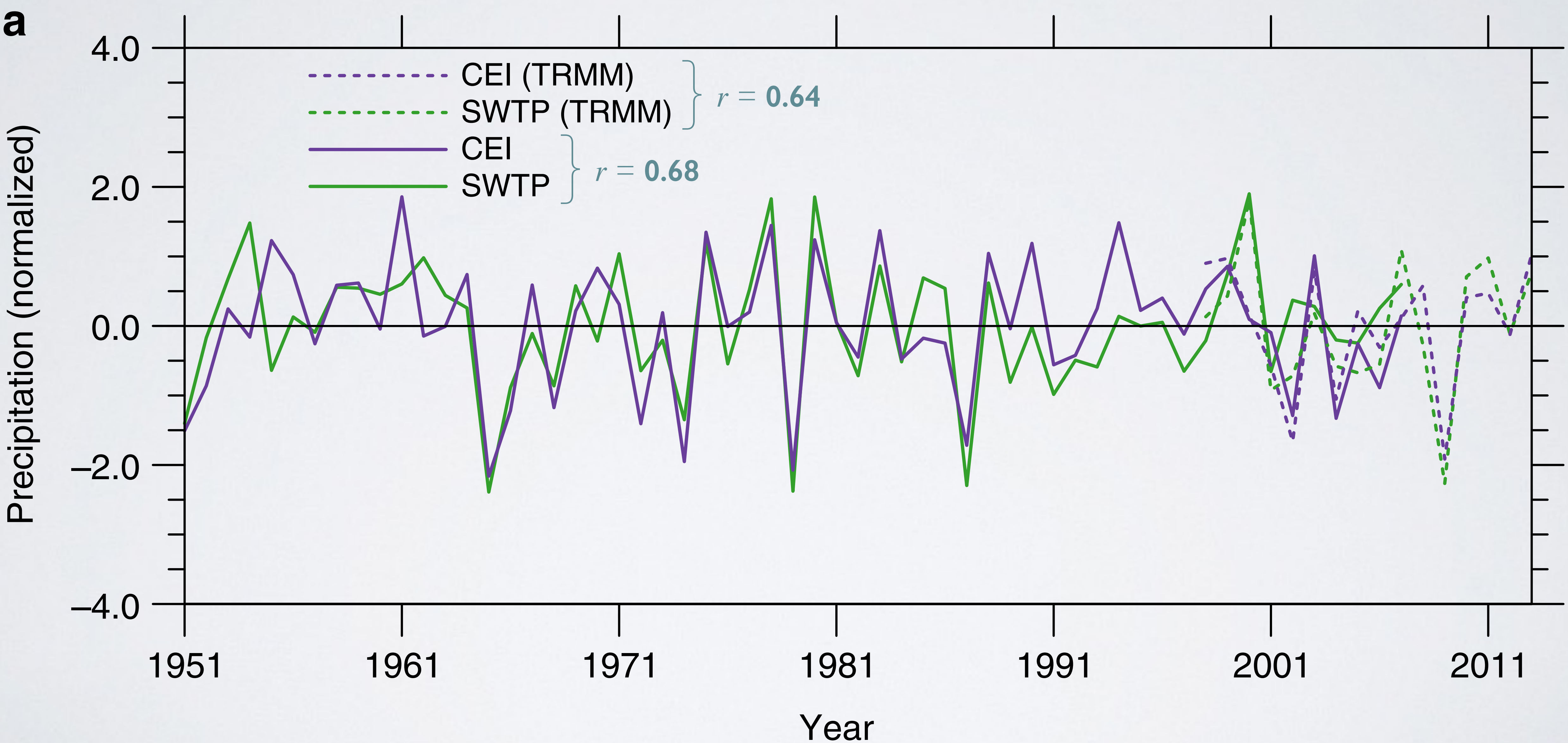
Temporal correlations:

Total summer precipitation over the SWTP is tightly correlated with total summer precipitation over CEI.



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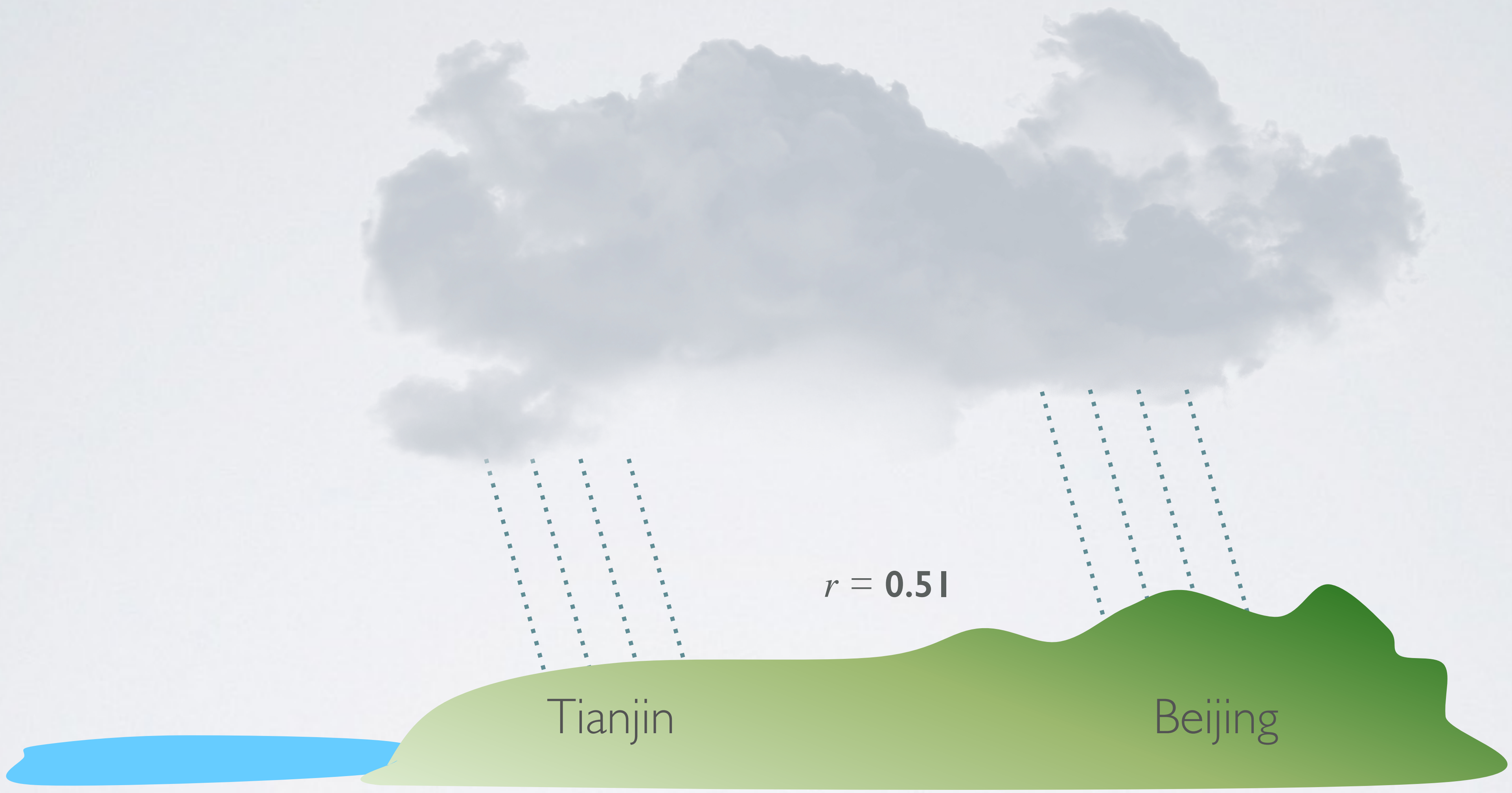
Context:

How tightly connected are JJAS rainfall in Beijing and Tianjin?



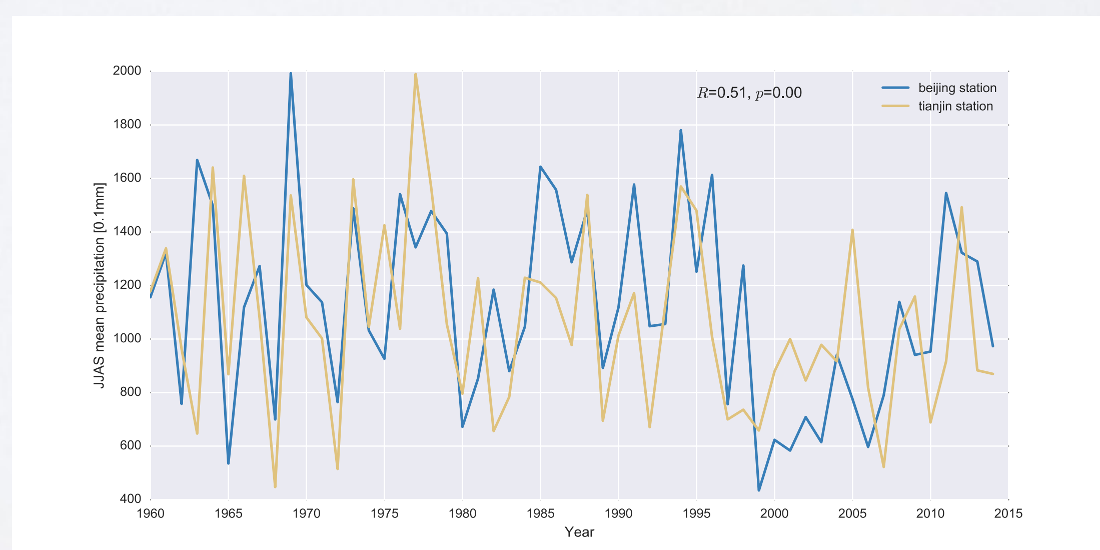
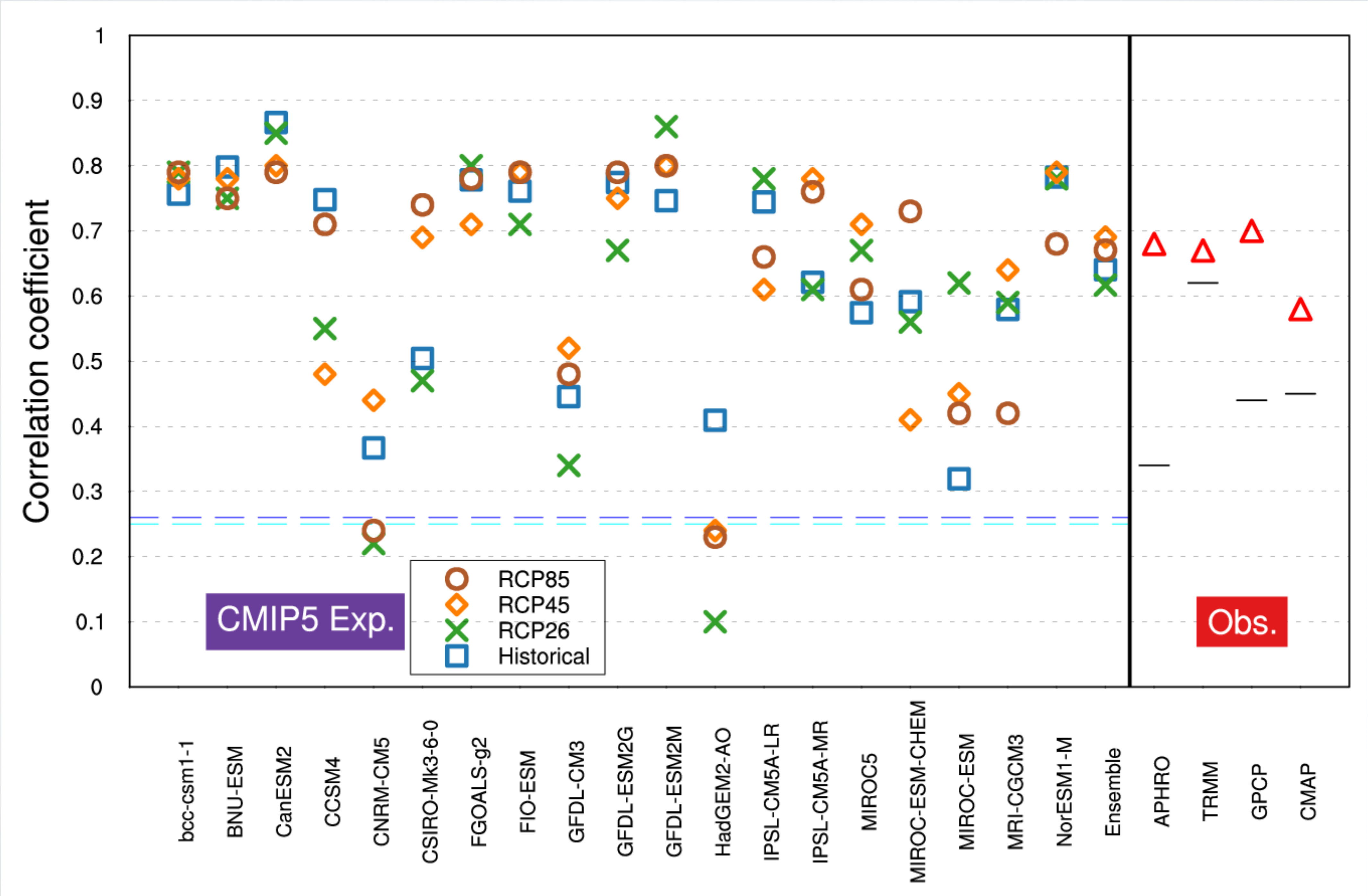


Figure courtesy of Lan Dai

Temporal correlations:

This tight relationship is robust among observational datasets and many CMIP5 models



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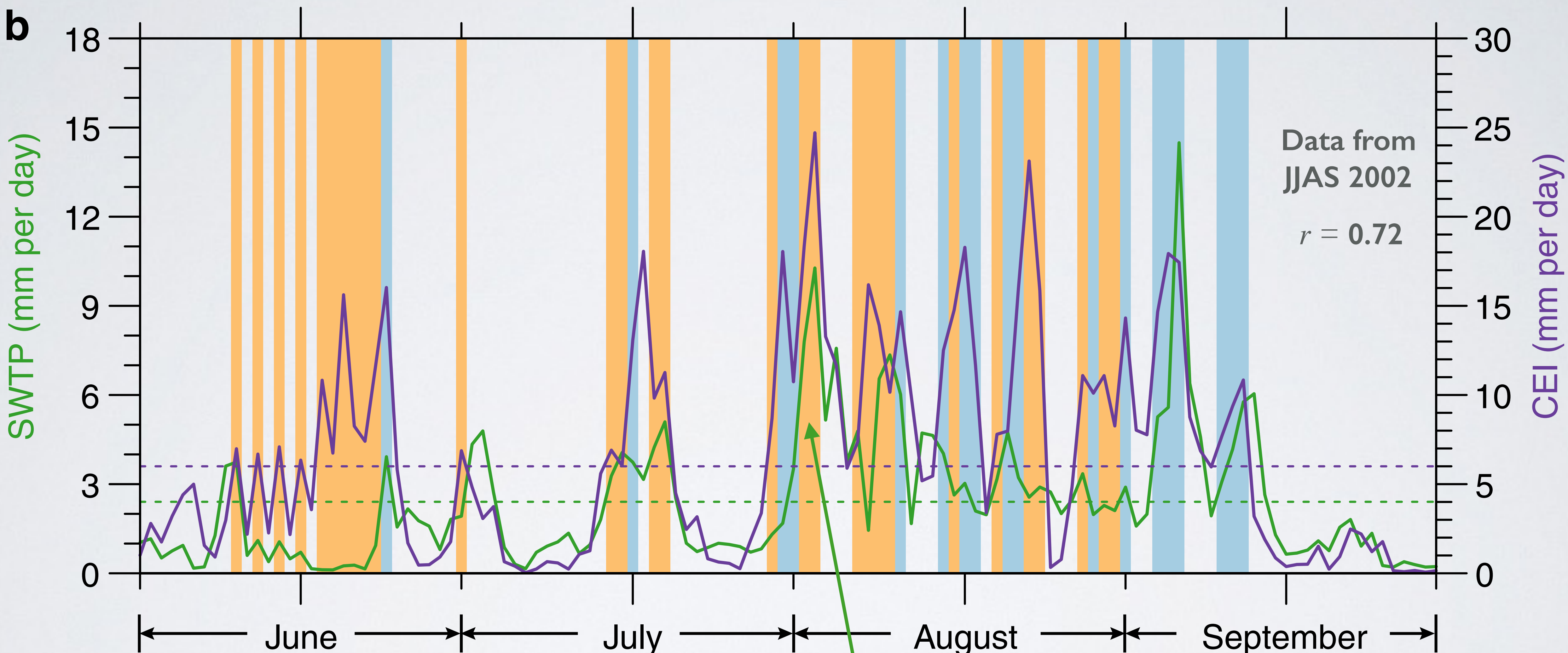
What maintains this relationship?

Examination of daily precipitation indicates that this co-variability is primarily determined by coherence between individual events



most large precipitation events over the SWTP occur in tandem with a corresponding event over CEI

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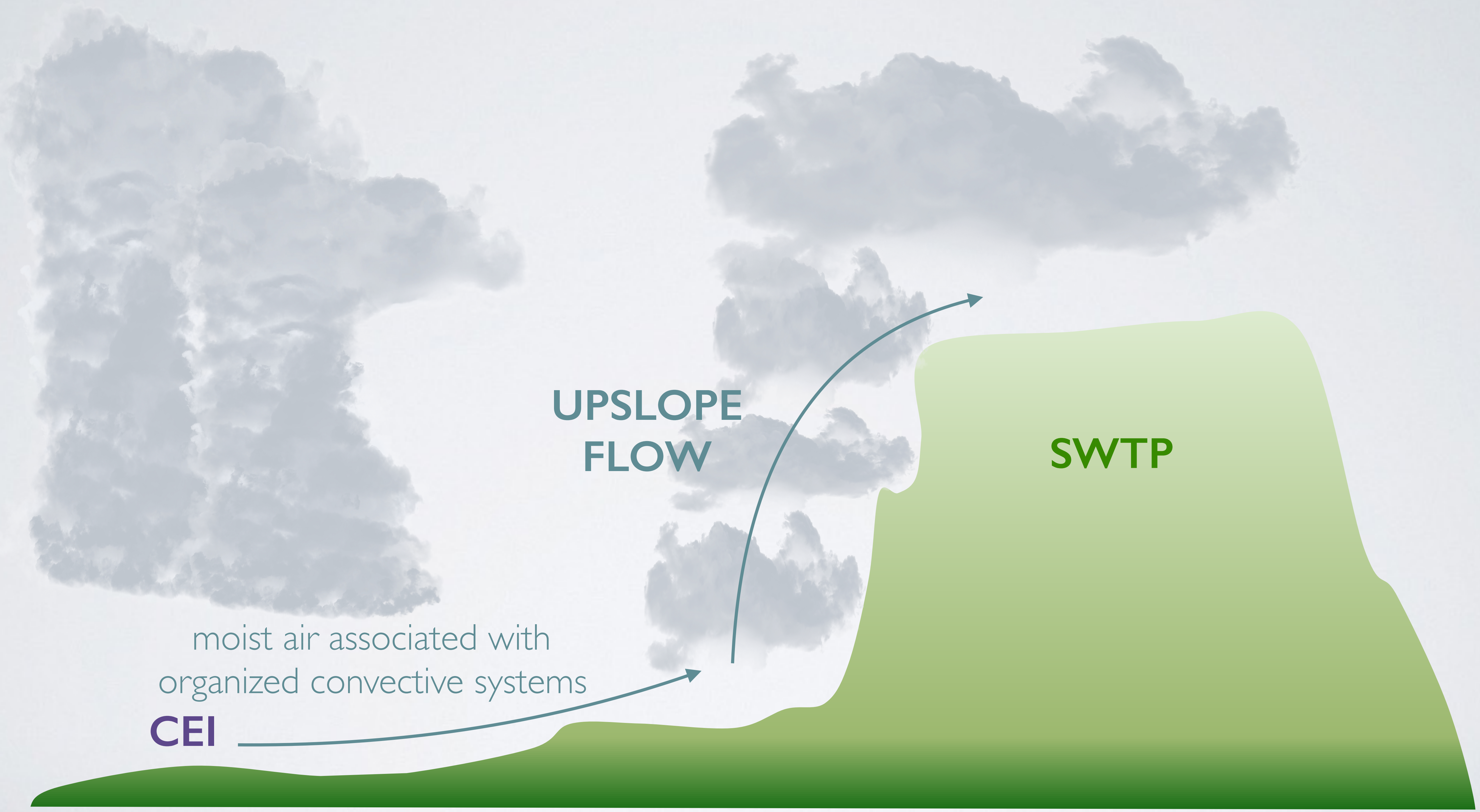
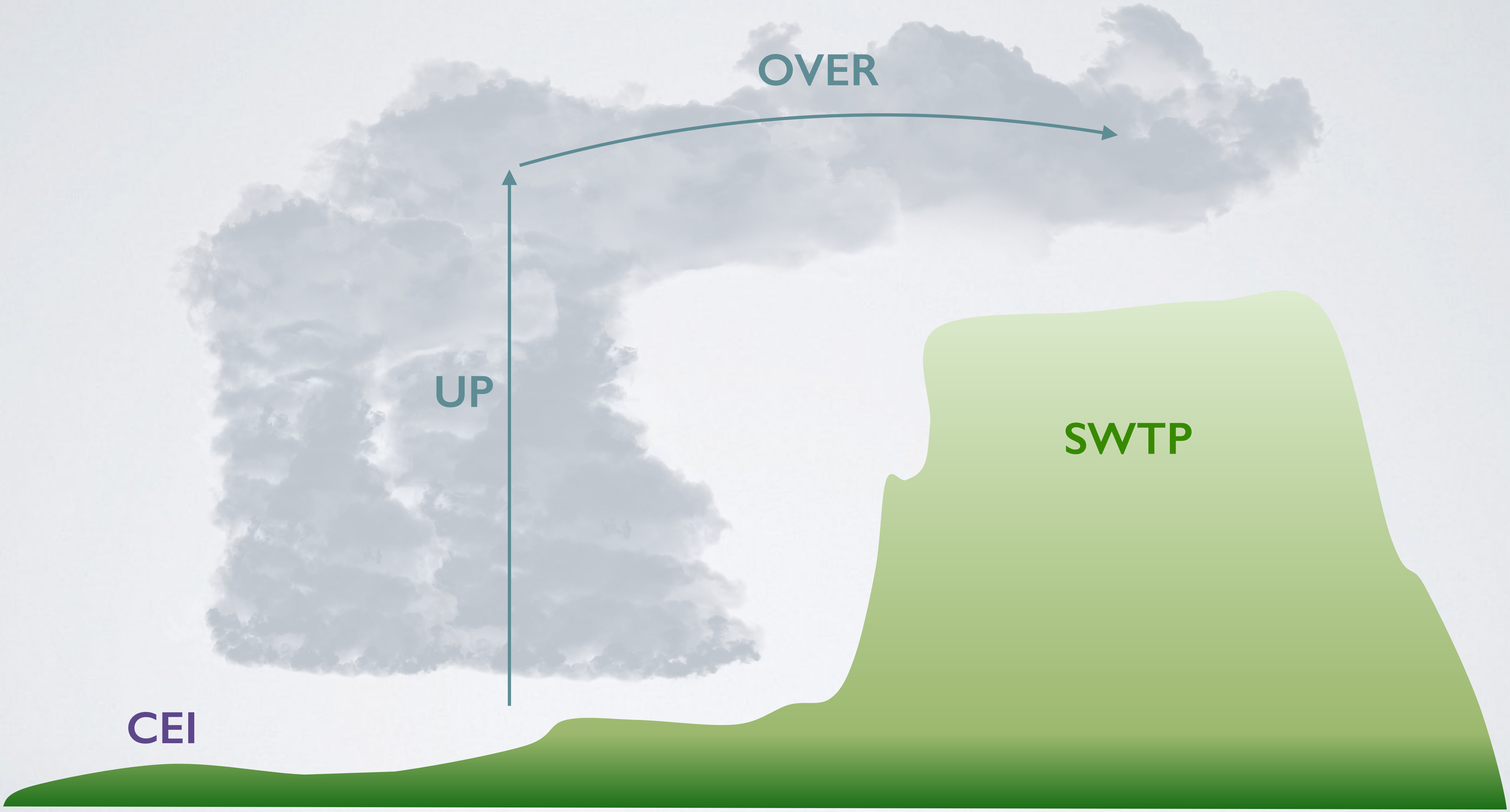
What is the mechanism?

(1) Upslope flow of moist air from CEI creates a link between wet conditions over CEI and wet conditions over SWTP



What is the mechanism?

(2) Deep convection over CEI delivers moist air and hydrometeors to the mid–upper troposphere, which are then swept over SWTP



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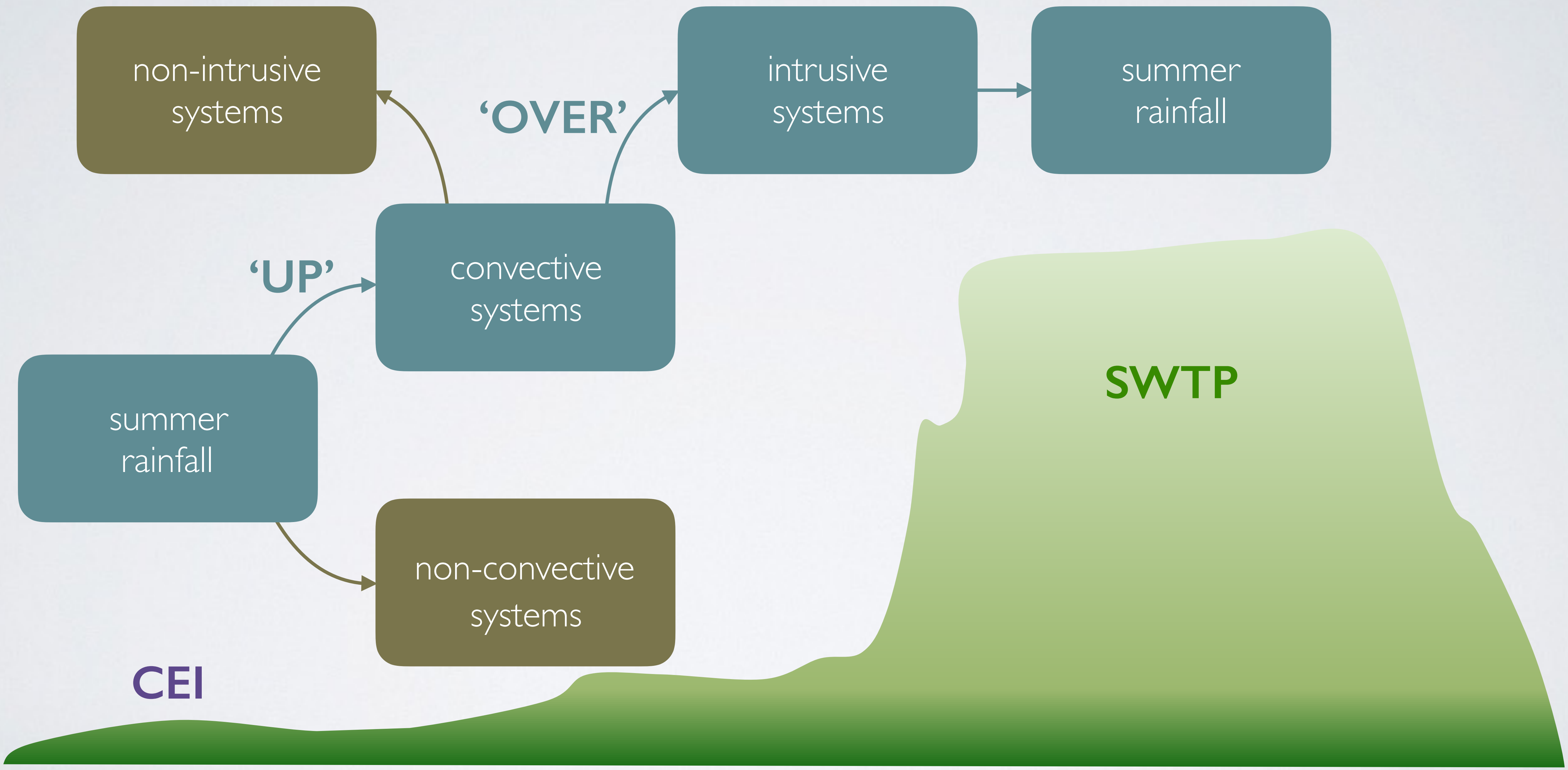
Our hypothesis:

The link stems primarily from up-and-over transport, which requires both convection over CEI and favorable upper level winds



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Step #1:

Identifying intrusive and non-intrusive cases

1. Convective systems are identified as contiguous areas larger than 10,000 km^2 with CLAUS brightness temperatures less than 219 K
2. Large rainfall events are defined as days with daily precipitation larger than 6 mm based on gridded TRMM data
3. Days that satisfy both criteria over CEI are defined as 'CS days'
4. CS days are classified into two types based on mid-tropospheric (400–600 hPa) meridional winds within 78–82°E and 26–32°N:
   - **intrusive CSs** are days with northward winds that exceed the seasonal mean (about 1 m s^{-1})
   - **non-intrusive CSs** are days with southward winds
5. The location and intensity of each CS are tracked using 850 hPa relative vorticity

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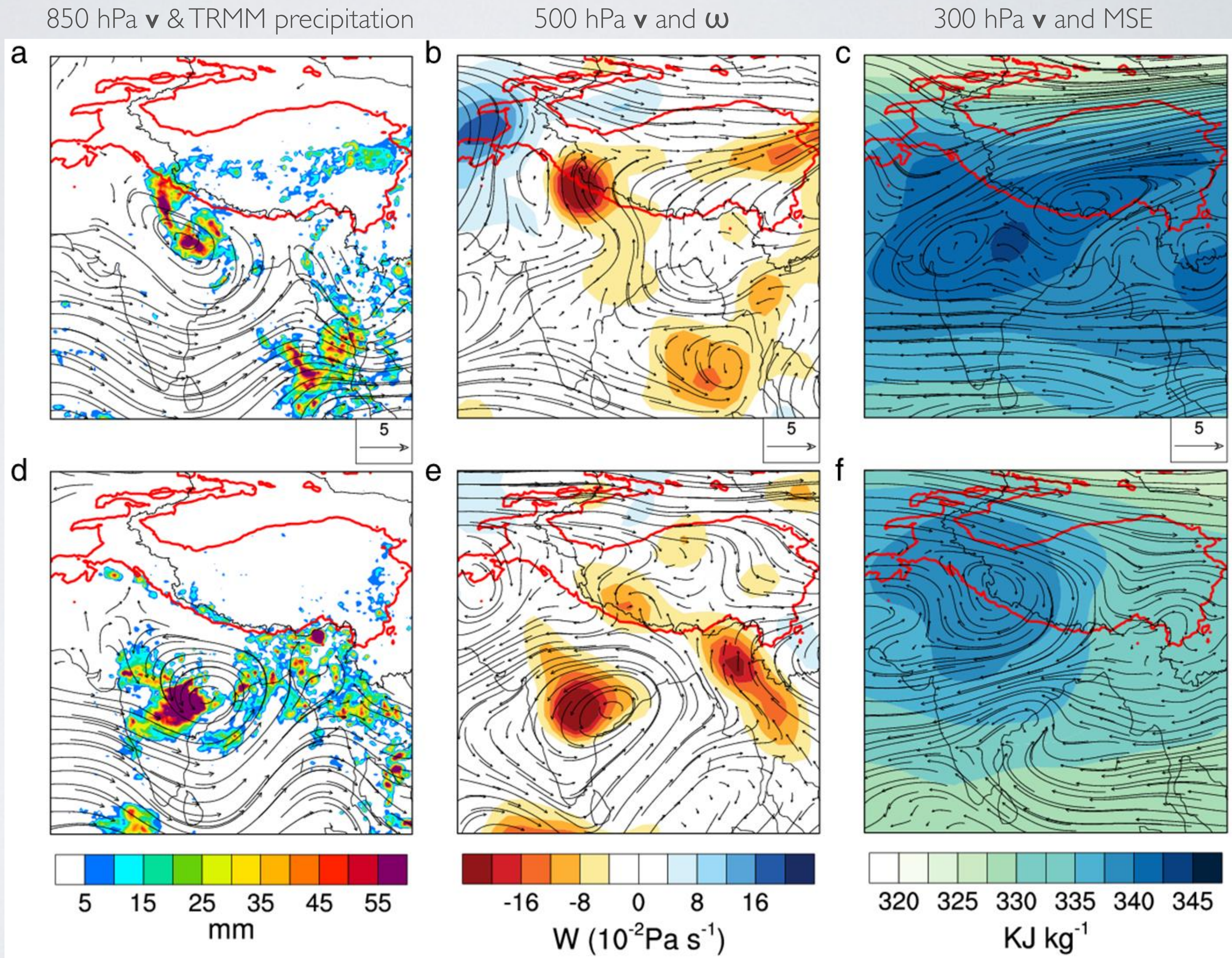
Step #1:
Identifying and examining intrusive and non-intrusive cases

an intrusive convective system

a non-intrusive convective system



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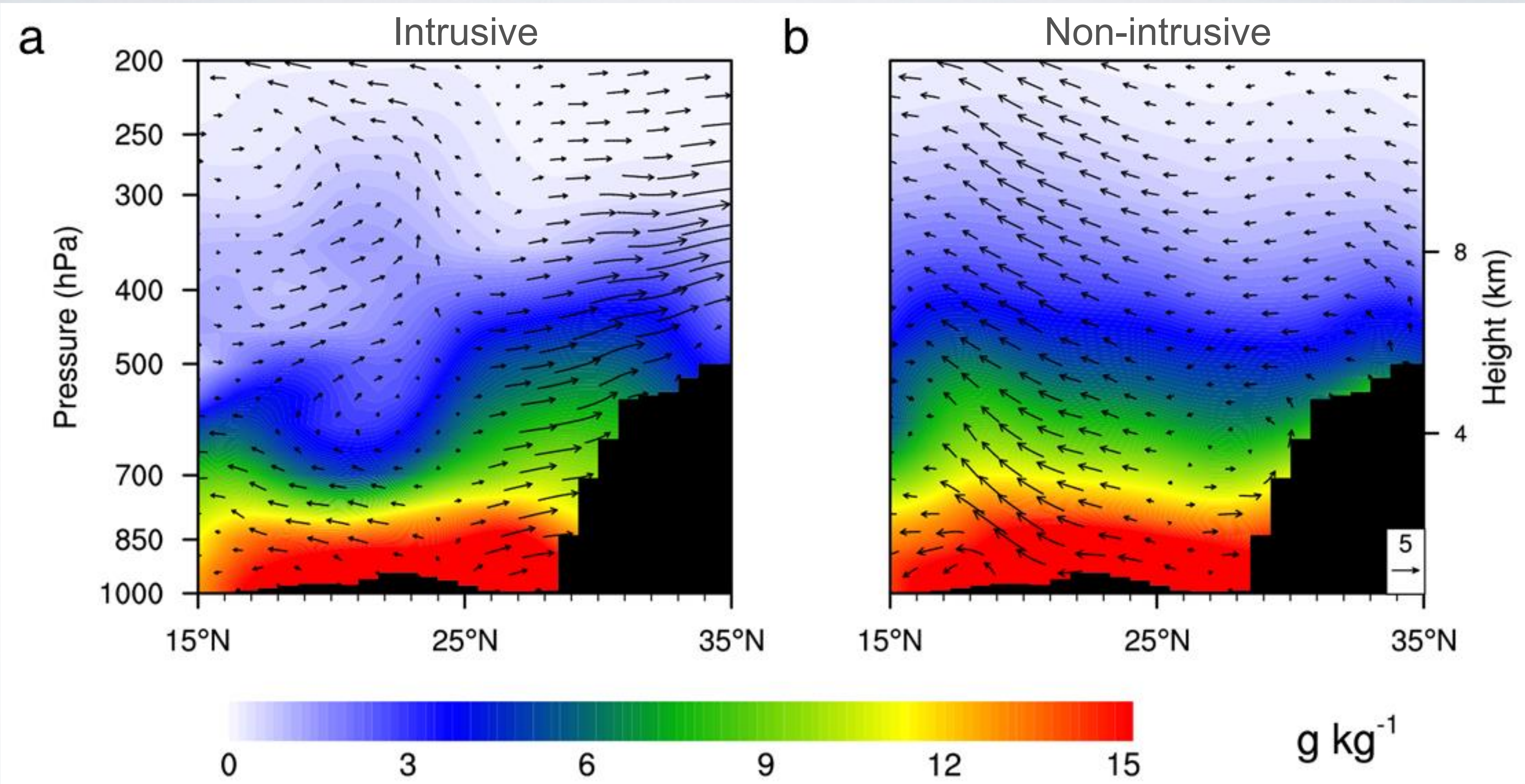
Vertical cross-sections:

Intrusive events moisten the upper levels and are associated with cross-mountain flow in the mid–upper troposphere; both upslope and up-and-over transport are enhanced during intrusive CSs



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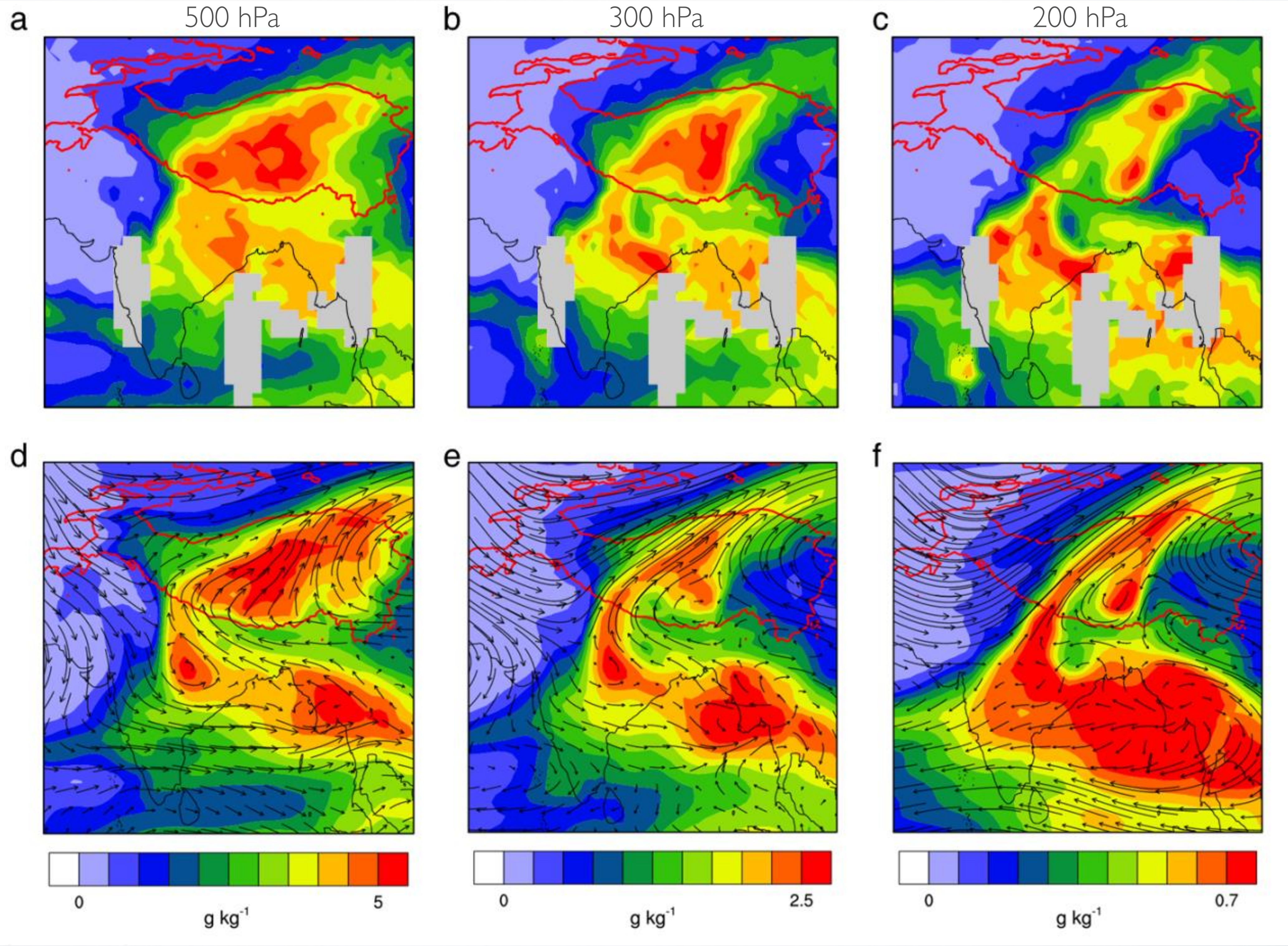
Step #2: establishing observational context

Is reanalysis data reliable for this purpose?

a single intrusive convective system

AIRS

ERA-Interim



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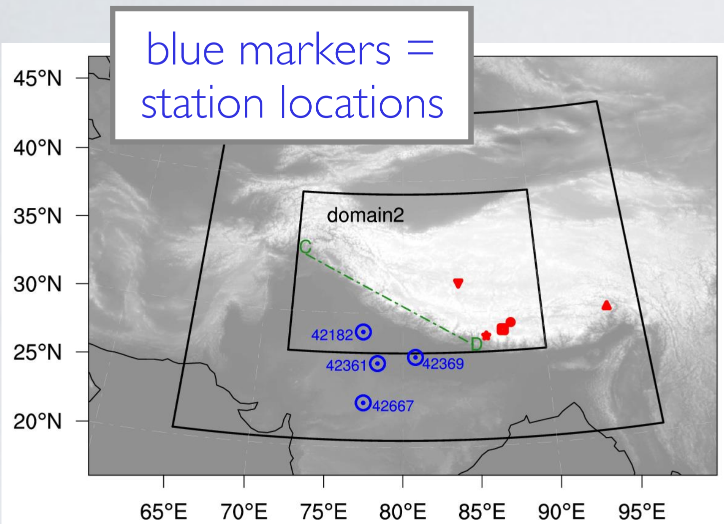
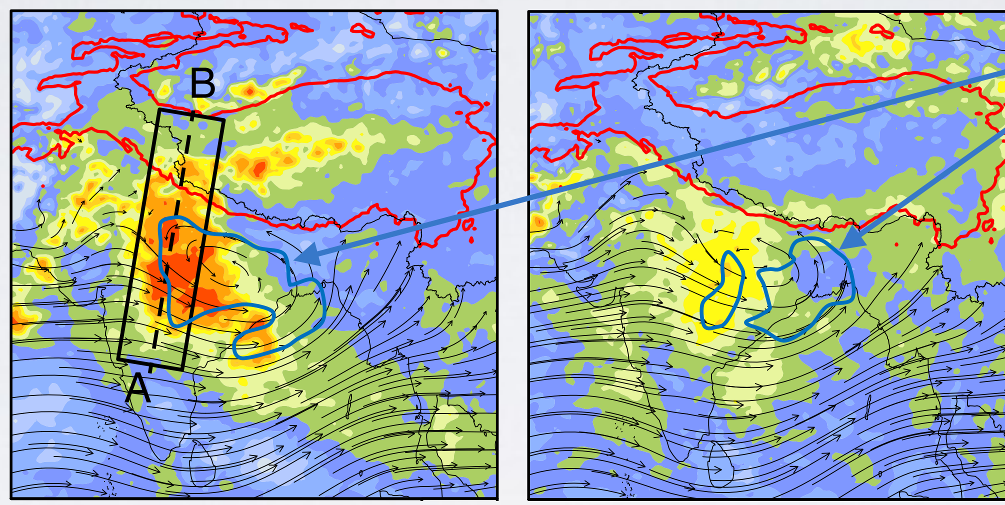
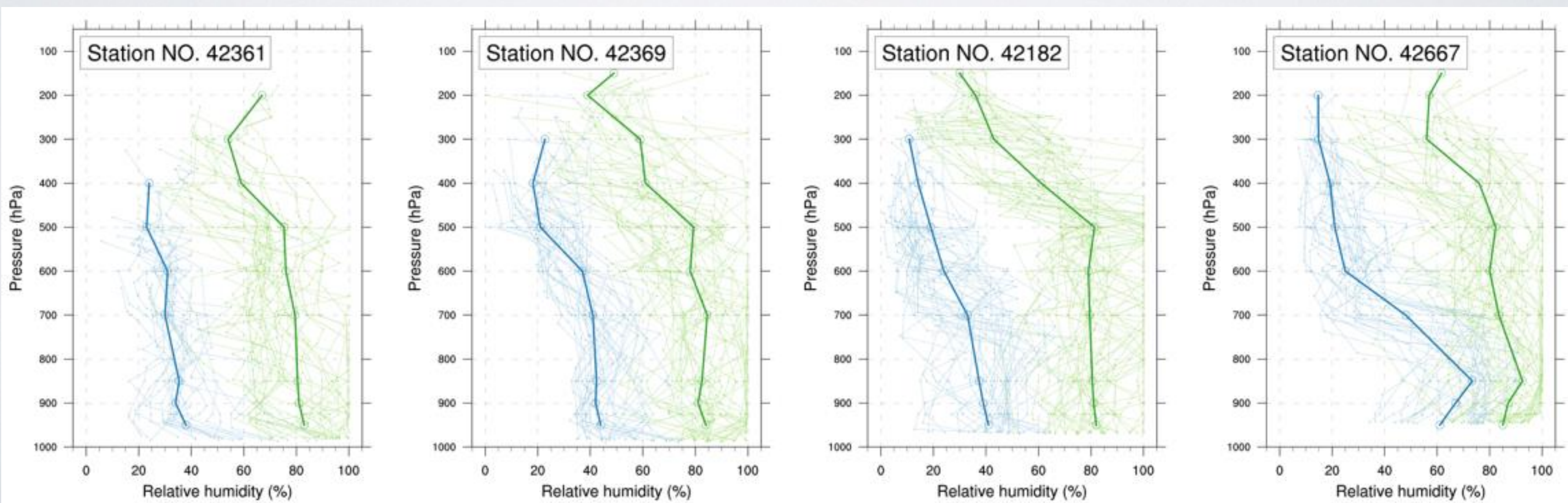
In situ observations:

Radiosonde profiles of relative humidity collected over CEI show evident differences between convective and non-convective days, particularly in the middle and upper troposphere







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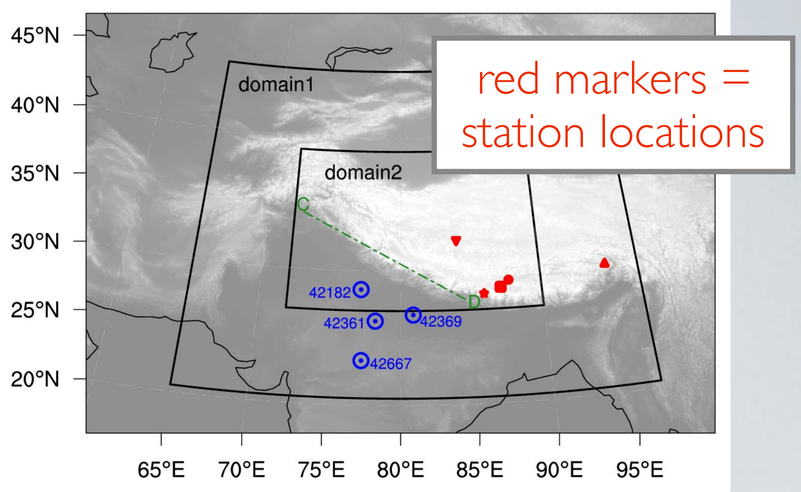
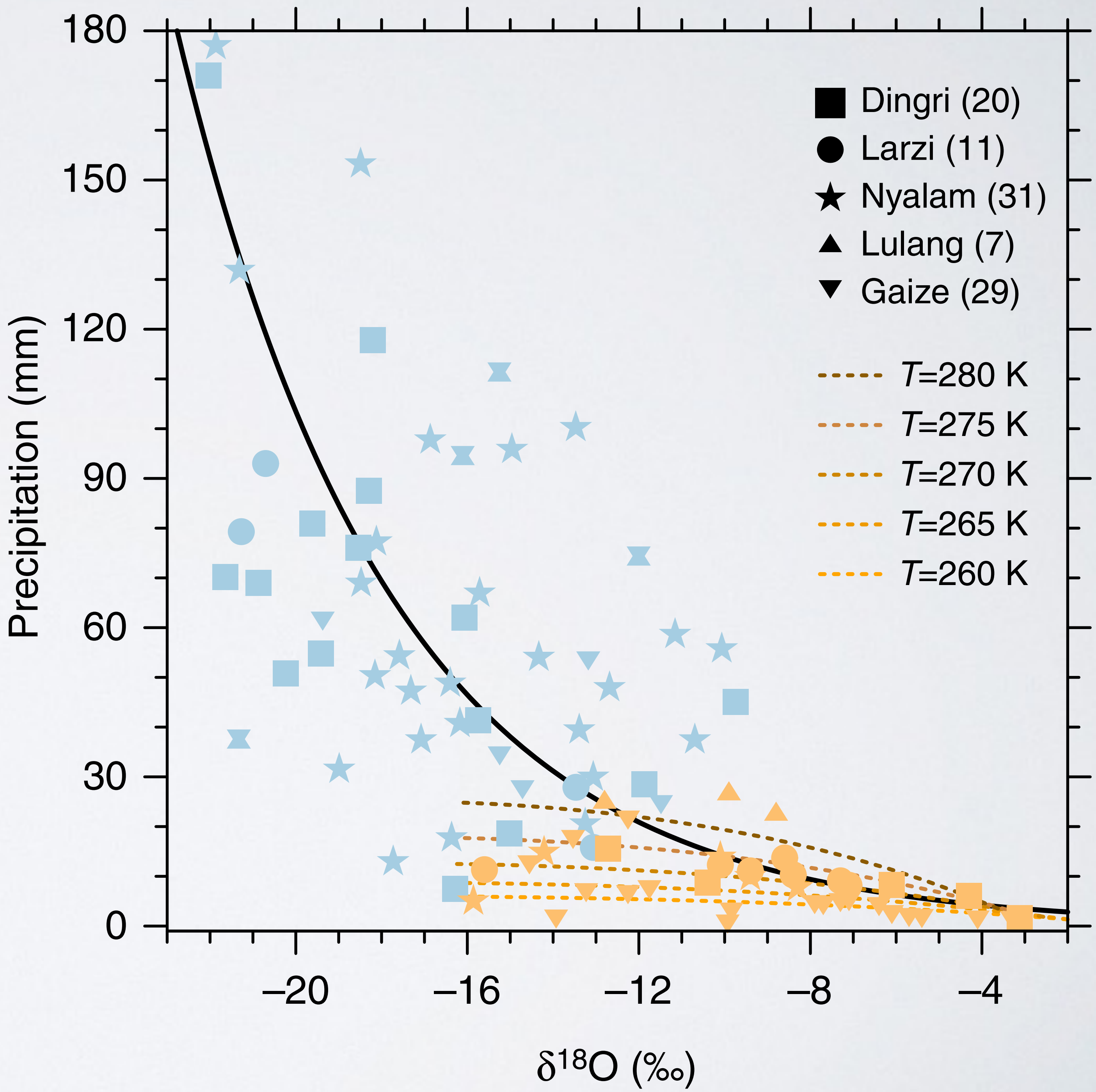
Isotopic ratios in precipitation:
59 intrusive cases and 39 non-intrusive cases

- Precipitation amount and δ^{18}O are inversely related
- Intrusive CSs (blue points) generate larger precipitation amounts with lower δ^{18}O
- The amount effect or differences in sources and/or transport? — can be differentiated by estimating variations of δ^{18}O with precipitation amount assuming local sources (dashed lines)
- Non-intrusive cases (when local sources are expected to dominate) are consistent with the theoretical model; intrusive cases are not
- Isotopic observations are therefore **consistent** with efficient moisture transport via the up-and-over route, and **inconsistent** with convective precipitation that depends on local recycling or upslope flow





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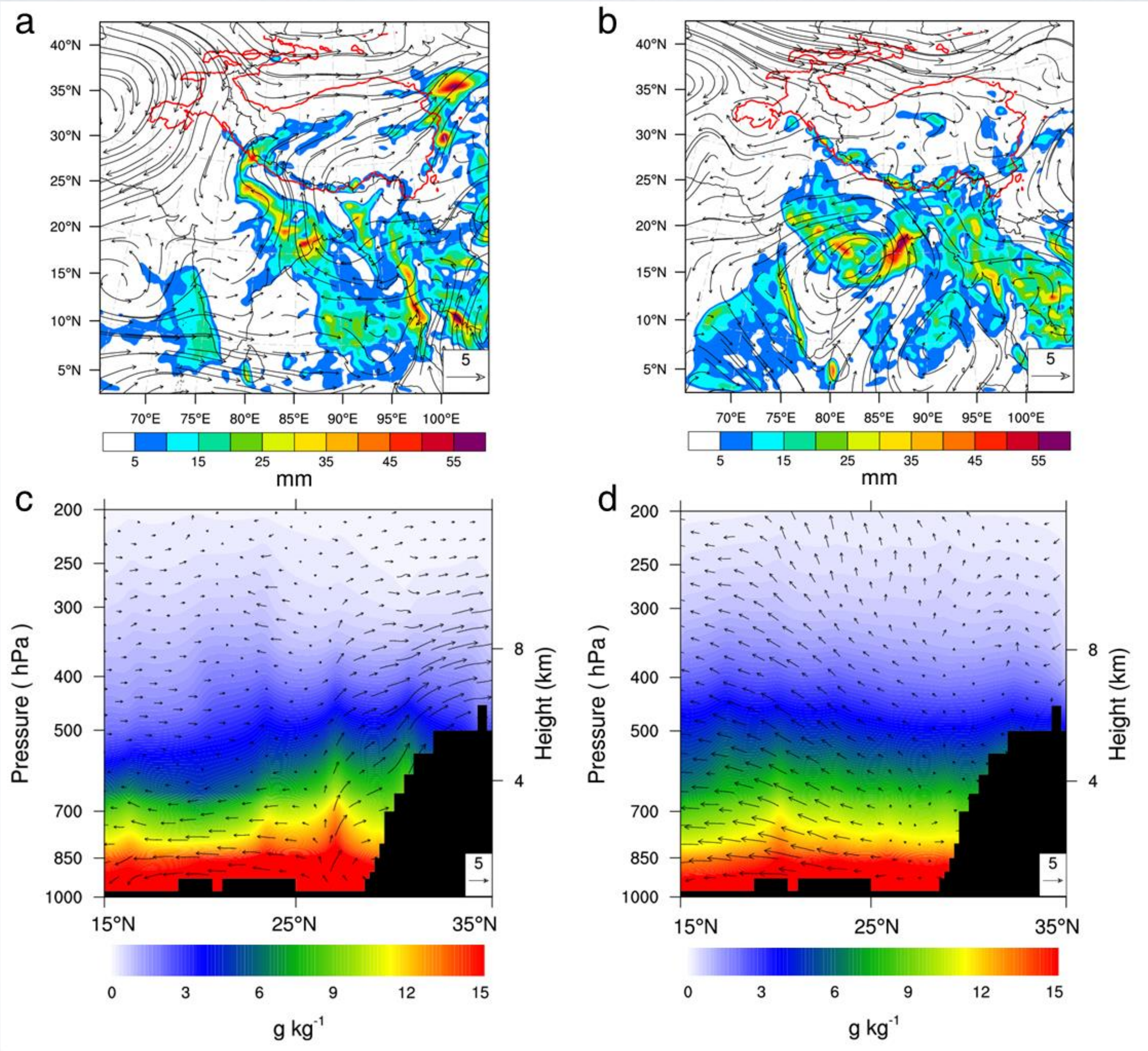
Step #3: further validation

Examination of alternative data sets: output from the High-Asia Refined analysis (HAR) is consistent with ERA-Interim and AIRS

an intrusive convective system



a non-intrusive convective system

HAR is based on WRF simulations using NCEP GFS dynamical fields

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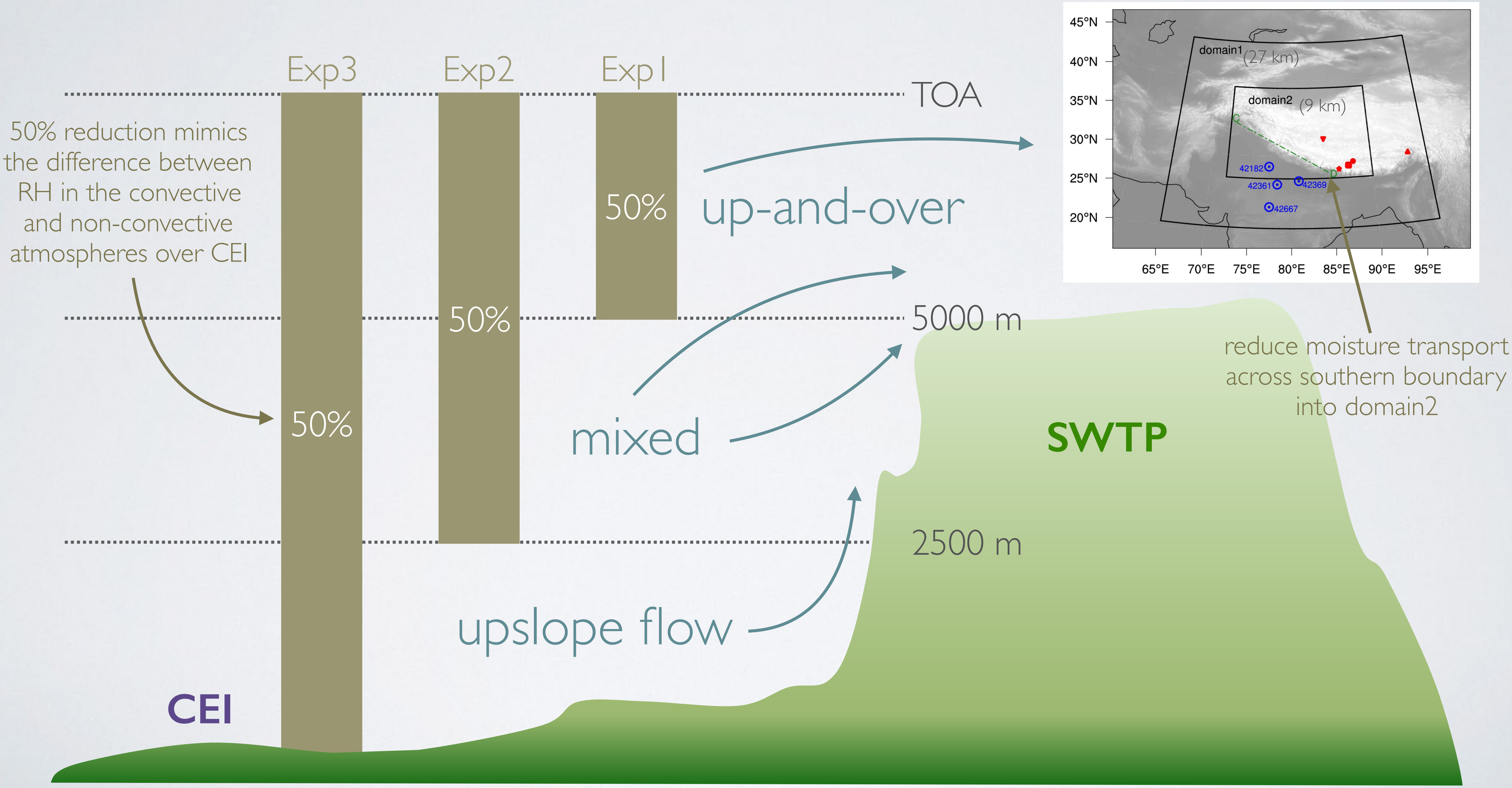
Step #4: quantification

To quantify the up-and-over contribution to precipitation over the SWTP, we run nested WRF simulations and cut moisture transport across the southern boundary by half in certain layers



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WRF sensitivity simulations:

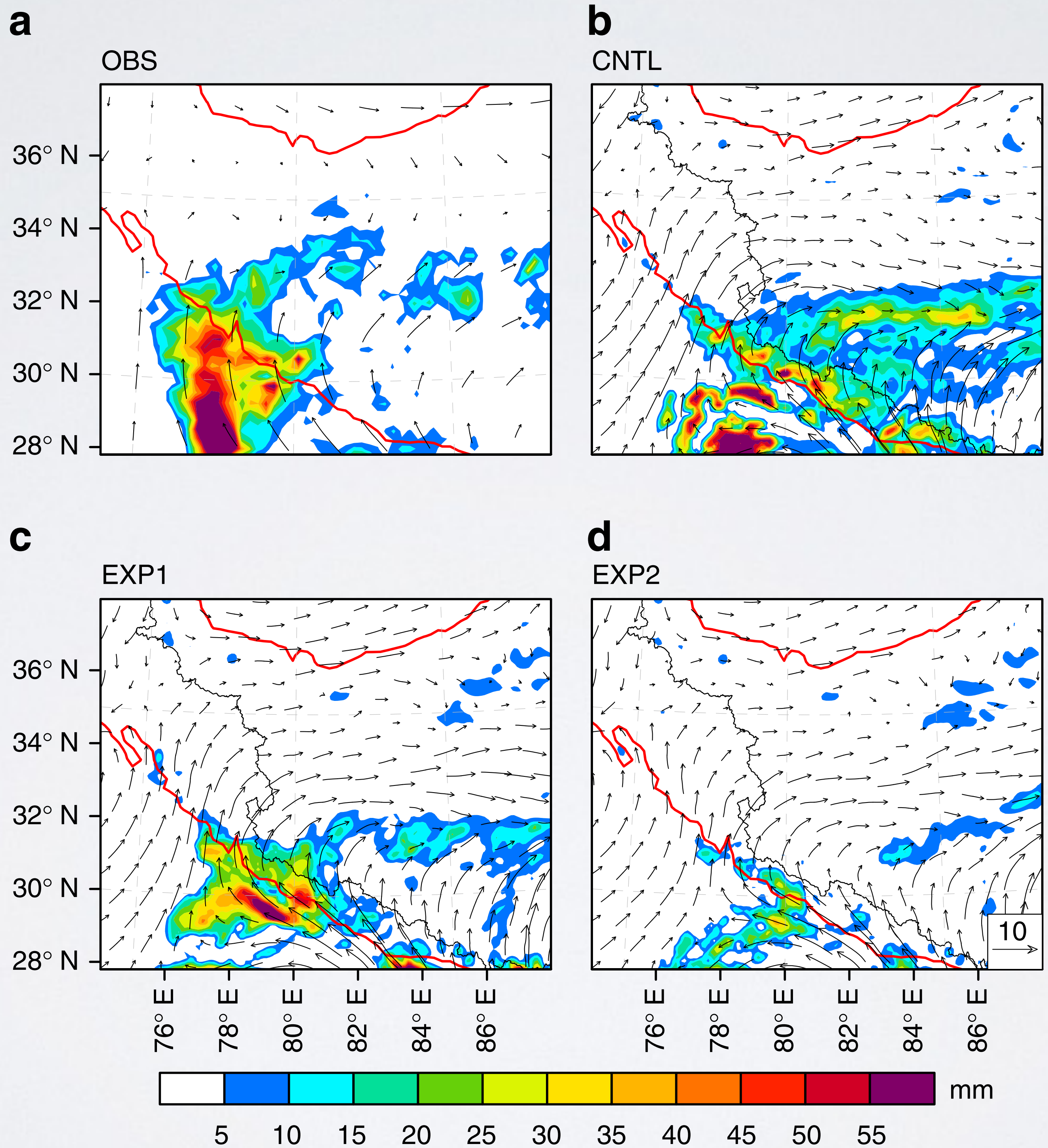
Sensitivity simulations indicate that 50~80% of precipitation during intrusive cases is due to up-and-over moisture transport

TRMM & ERA-Interim

WRF control simulation

Moisture transport reduced by 50% above 5 km agl: P ~44%

Moisture transport reduced by 50% above 2.5 km agl: P ~18%



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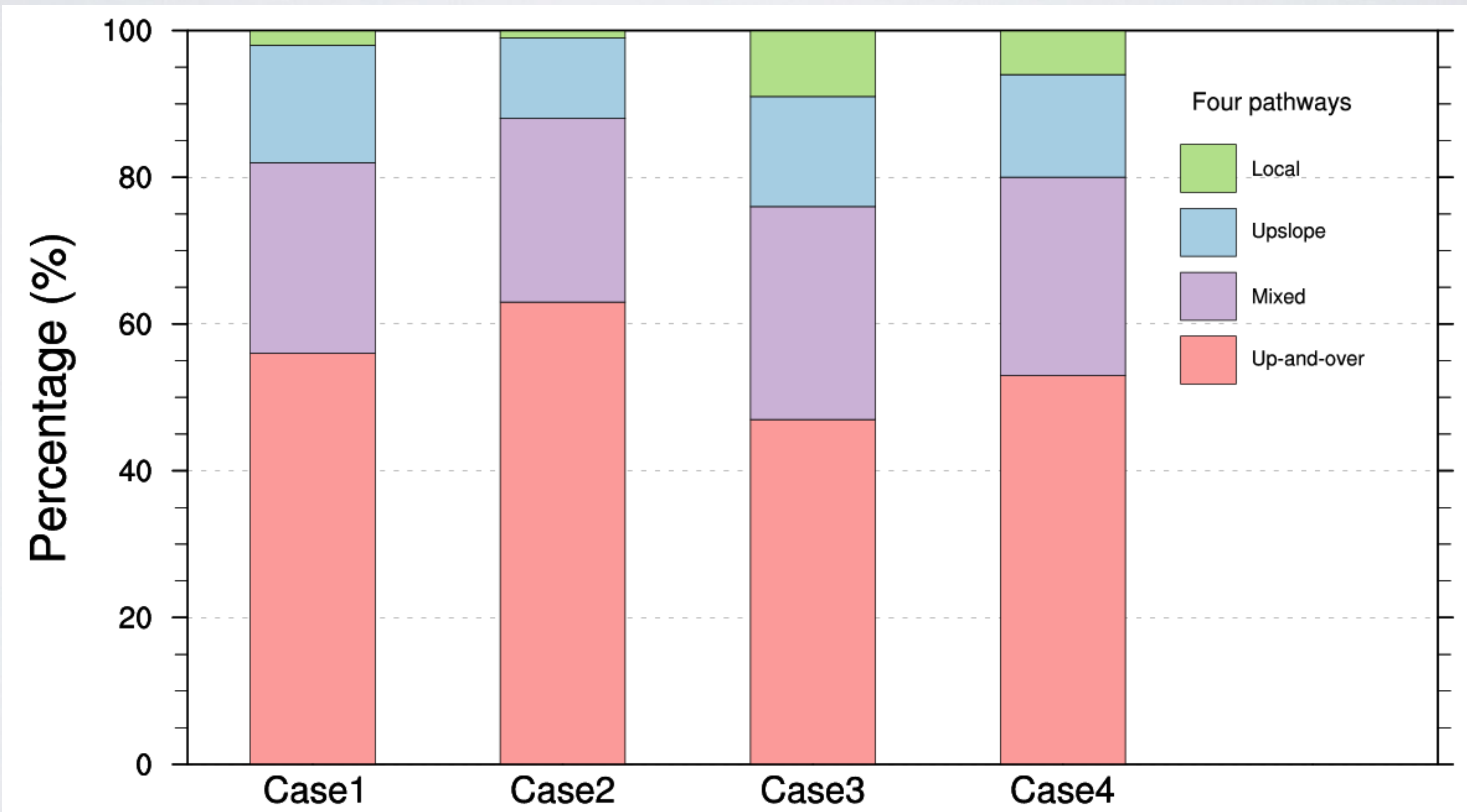
WRF sensitivity simulations:

These results (50~80%) are consistent for four randomly selected intrusive cases, suggesting that these numbers are relatively robust among individual intrusive CSs



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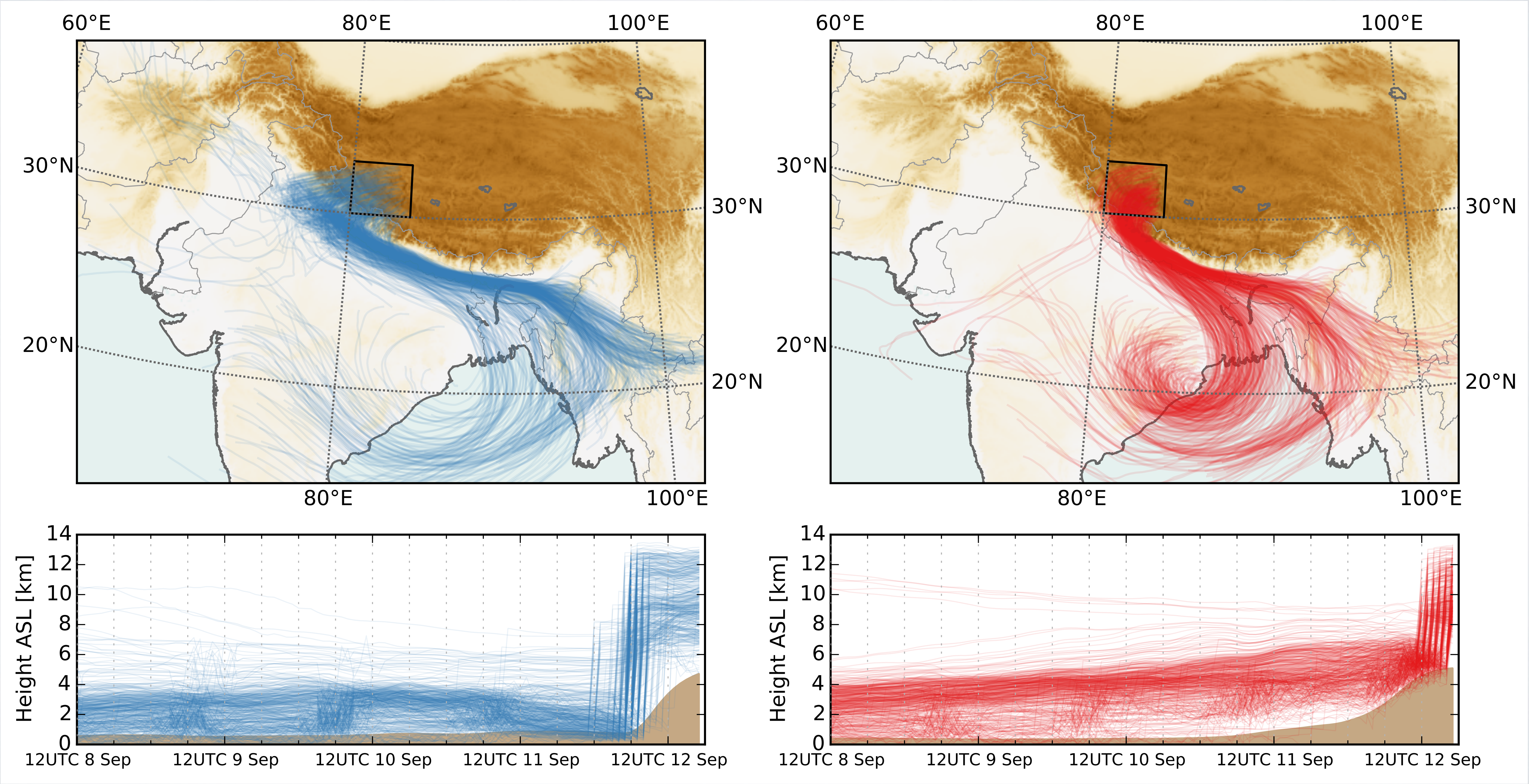
FLEXPART back trajectories:

Trajectory model simulations using FLEXPART also assign 50~75% of likely "rain particles" to up-and-over transport during intrusive cases

up-and-over

upslope flow / local recycling



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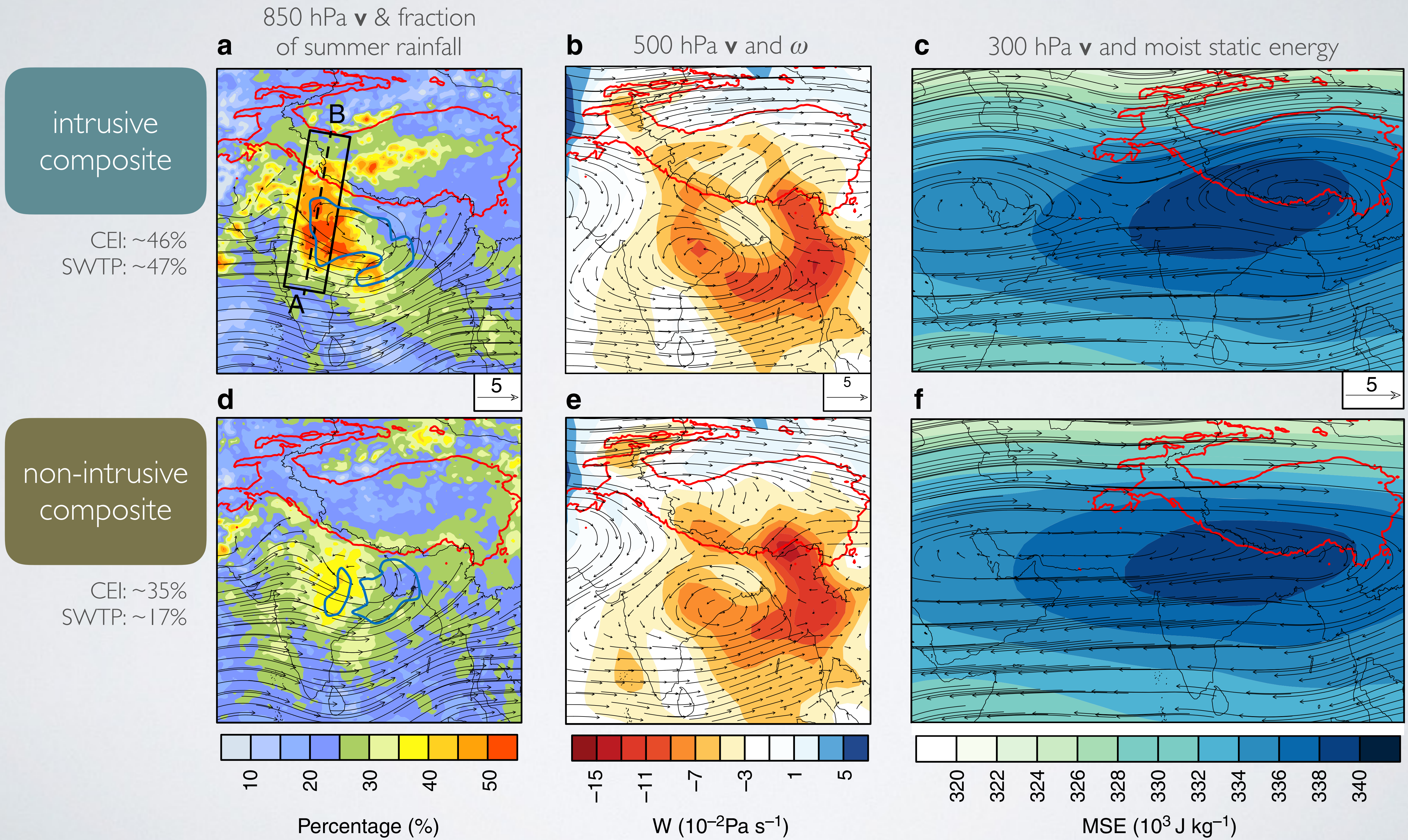
Step #5: composite analysis

About half of all convective events over CEI are intrusive, and these account for about half of summer rainfall over the SWTP



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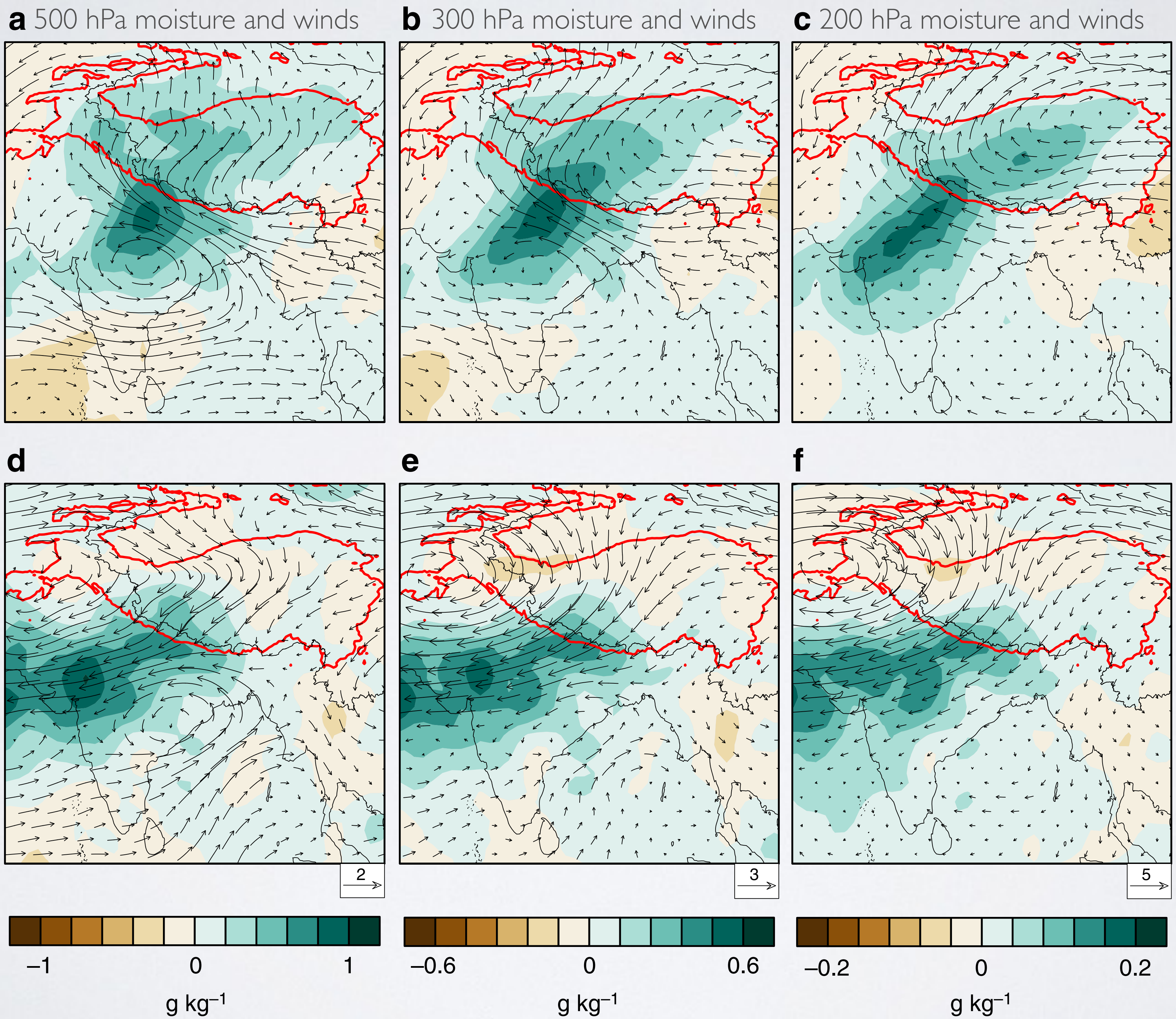
Satellite observations:

AIRS observations support the hypothesis that upper tropospheric moisture transport is enhanced during intrusive CSs

intrusive composite

non-intrusive composite



Anticyclone:
Tibetan Plateau mode — northward over SWTP

Anticyclone:
Iranian Plateau mode — southward over SWTP

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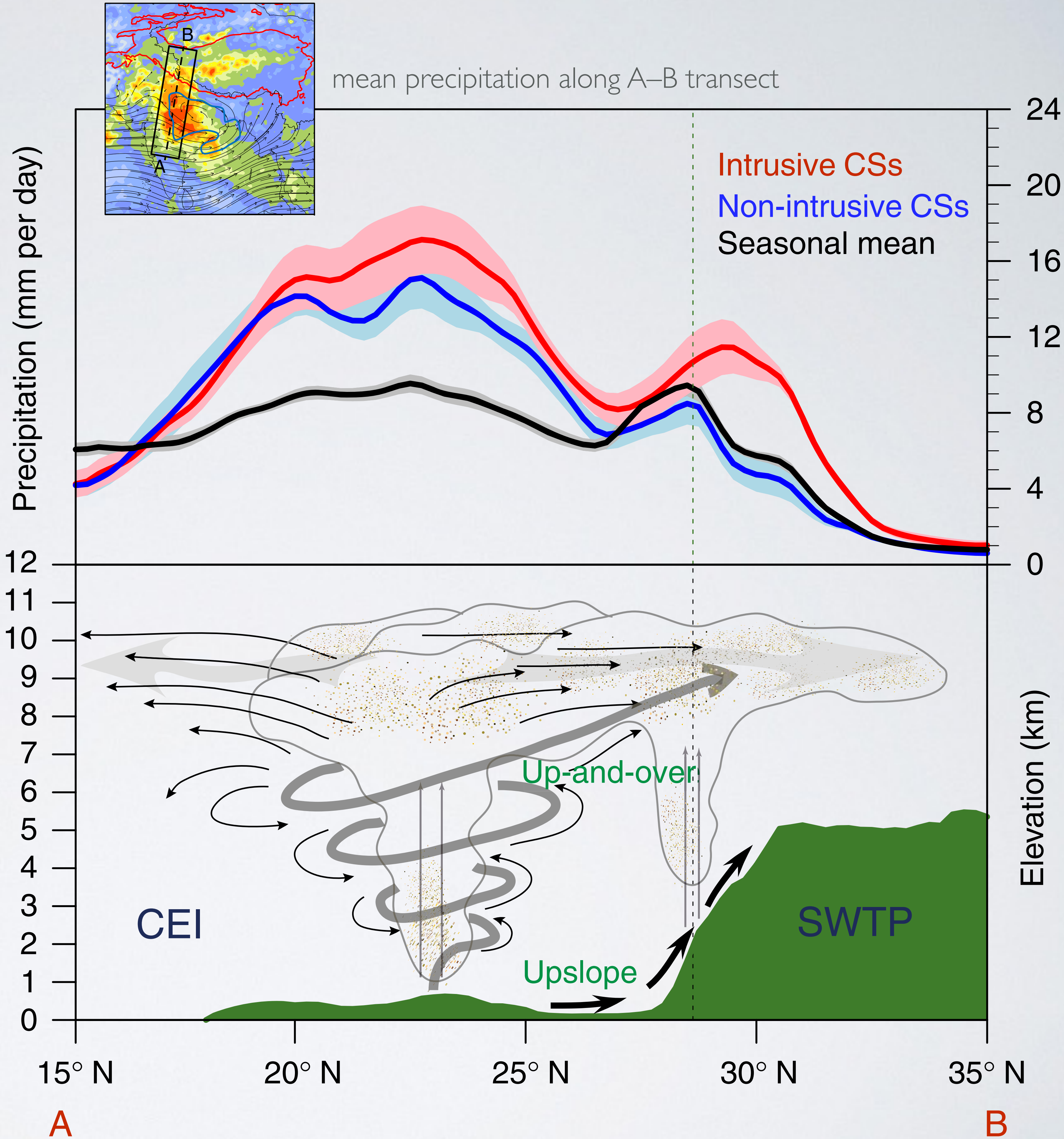
Summary:

- We find a strong connection between summer rainfall over CEI and over SWTP at multiple time scales, despite the topographic barrier
- This link is maintained by convection over CEI (up) and transport in the middle–upper troposphere (over)
- Intrusive CSs contribute half of summer rainfall over the SWTP, of which 50~80% is supplied via the up-and-over moisture transport route
- SWTP rainfall far exceeds the seasonal mean during intrusive CSs, when the up-and-over route is "open"
- Rainfall rarely passes beyond the plateau flank during non-intrusive CSs, when the up-and-over route is "closed"



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Further thoughts:

Episodes of local convection over the SWTP often occur in the days following intrusive CS events, suggesting that the role of up-and-over transport also extends to supplying moisture for local precipitation recycling processes. In this sense, intrusive CSs over CEI and associated up-and-over transport fundamentally determine the overall wetness of the SWTP: without this source, the SWTP would be substantially drier.

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Key message:

The direct dynamical link between summer precipitation over CEI and summer precipitation over SWTP provides valuable context for evaluating projections and reconstructions of climate change in this region, and for assessing the resilience of the SWTP biosphere, hydrosphere, and cryosphere.

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