Observed Water Vapor Budget in an Atmospheric River over the Northeast Pacific

Joel Norris

AMS Annual Meeting

January 7, 2019

Center for Western Weather and Water Extremes

SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

Collaborators

- Reuben Demirdjian
- Forest Cannon

- Marty Ralph, Byron Blomquist, Christopher Fairall, Paul Neiman, Ryan Spackman, Simone Tanelli, and Duane E. Waliser

CalWater paper

- Ralph, F.M, K. A. Prather, D. Cayan, J.R. Spackman, P. DeMott, M. Dettinger, C. Fairall, R. Leung, D. Rosenfeld, S. Rutledge, D. Waliser, A. B. White, J. Cordeira, A. Martin, J. Helly, and J. Intrieri, 2016: CalWater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in Modulating U.S. West Coast Precipitation in a Changing Climate. Bull. Amer. Meteorol. Soc., 97, 1209-1228.

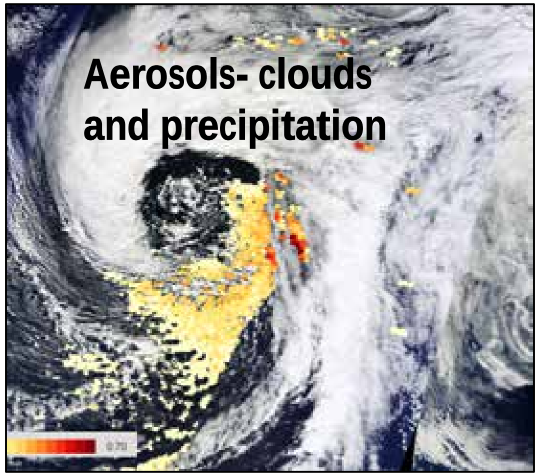
“CalWater – 2015” Field Experiment on Atmospheric Rivers & Aerosols

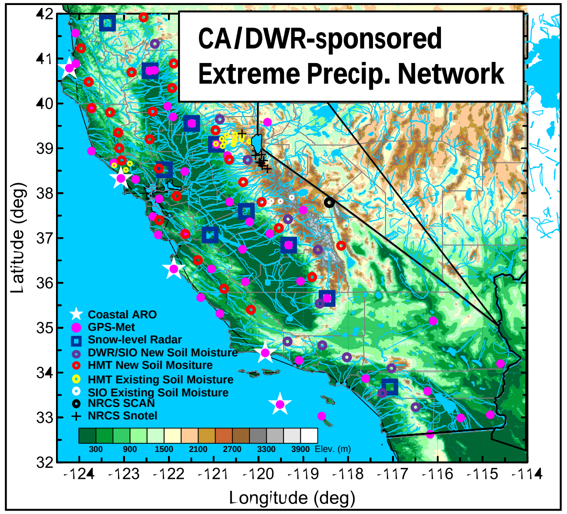
Steering Committee

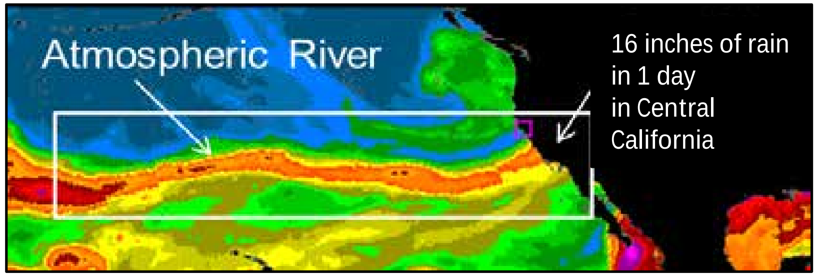
Co-Chairs: F.M. Ralph
K. Prather, D. Cayan of USCD
+ NOAA, DOE, USGS, NASA
and other Univ. members

Atmospheric Sci., Chemistry,
Hydrology, Oceanography

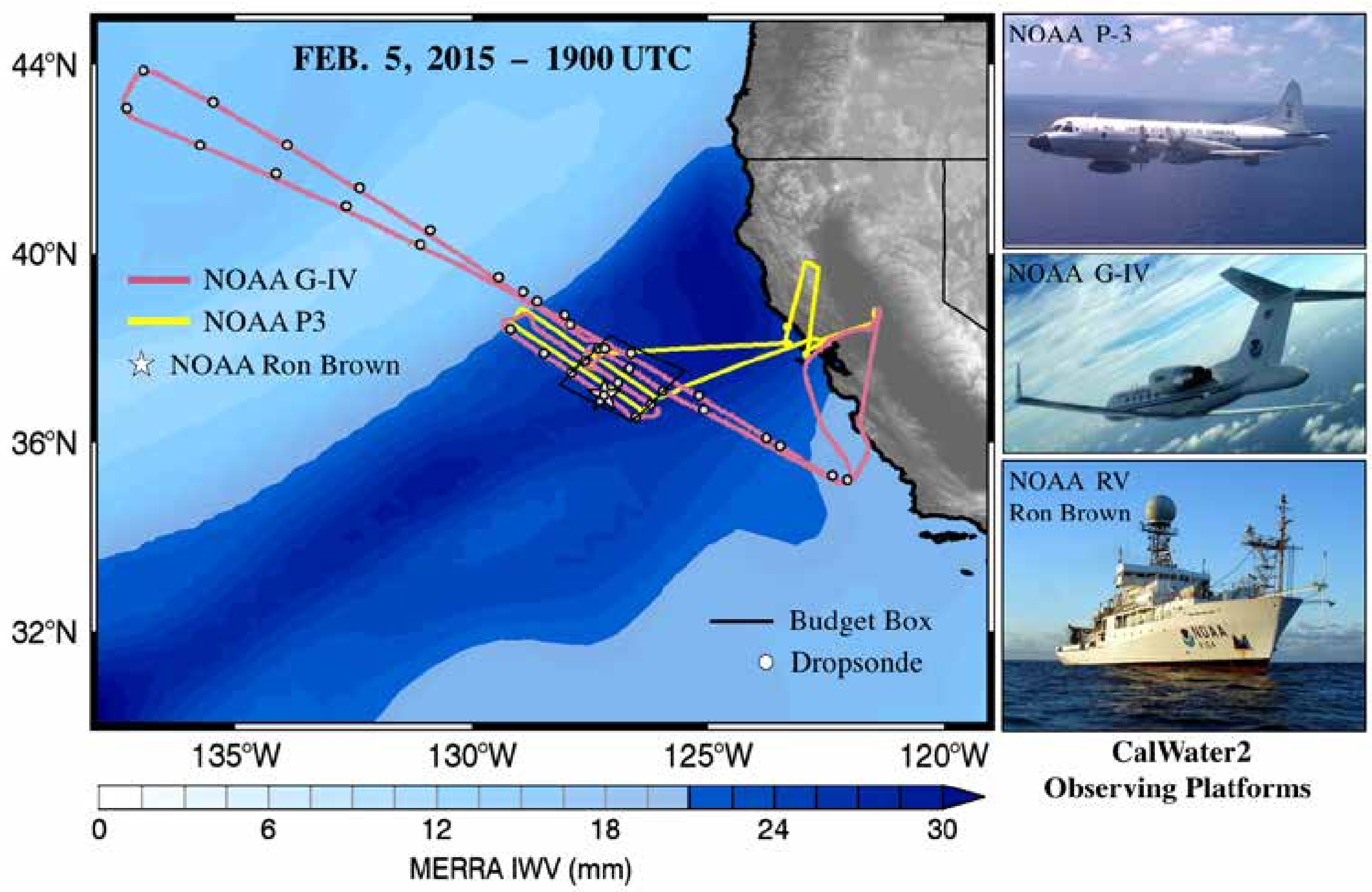
Ralph et al. 2016
Bull. Amer. Meteor. Soc.







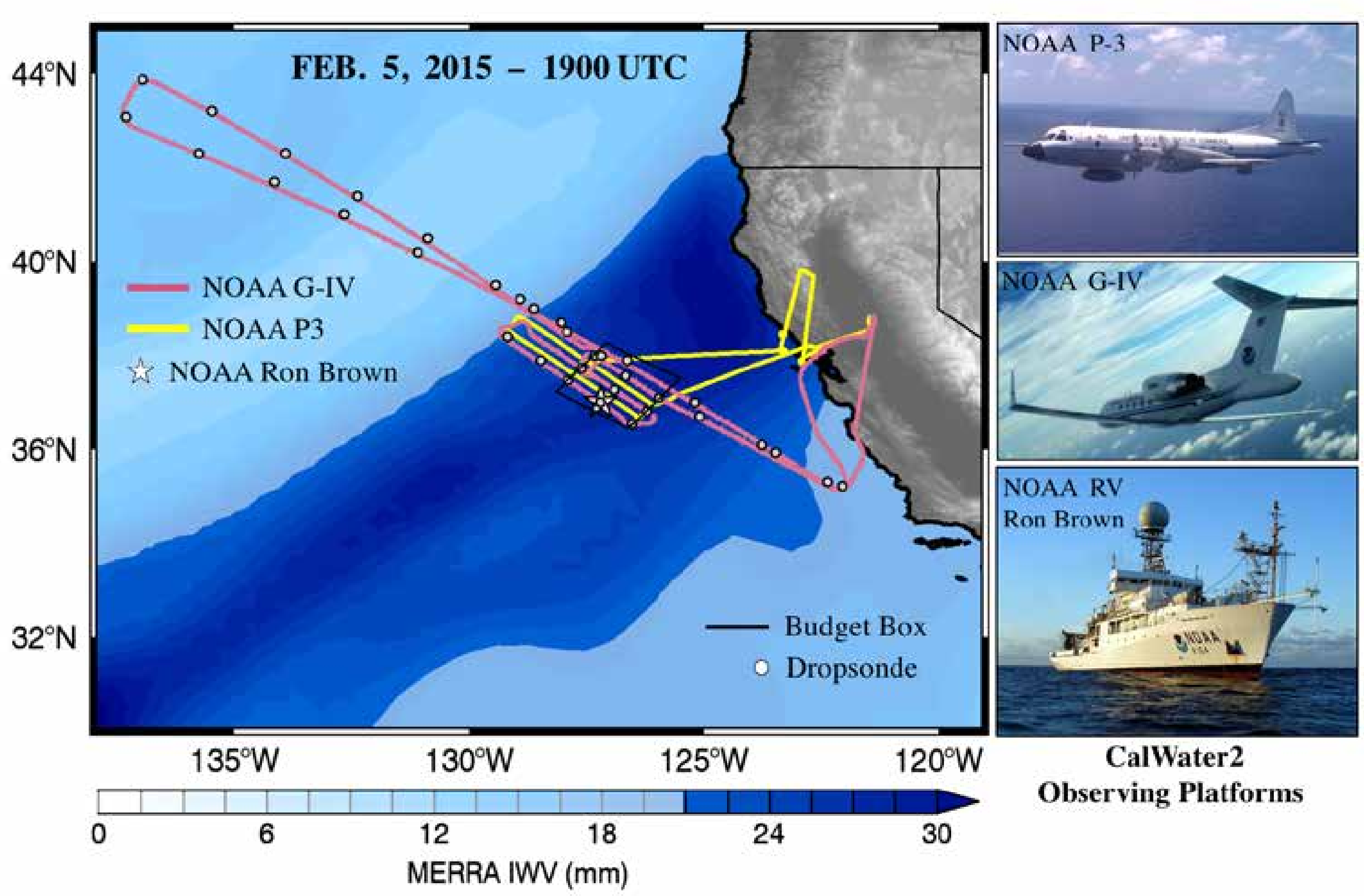
CalWater2 Observations on 5 February 2015



CalWater2
Observing Platforms

Dropsondes
Measured: z, p, T, RH, ***V***
Derived: mass flux, moisture flux, IWV

CalWater2 Observations on 5 February 2015



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Satellite (SSMIS)
Retrieved: IWV, precipitation (only for pattern matching)

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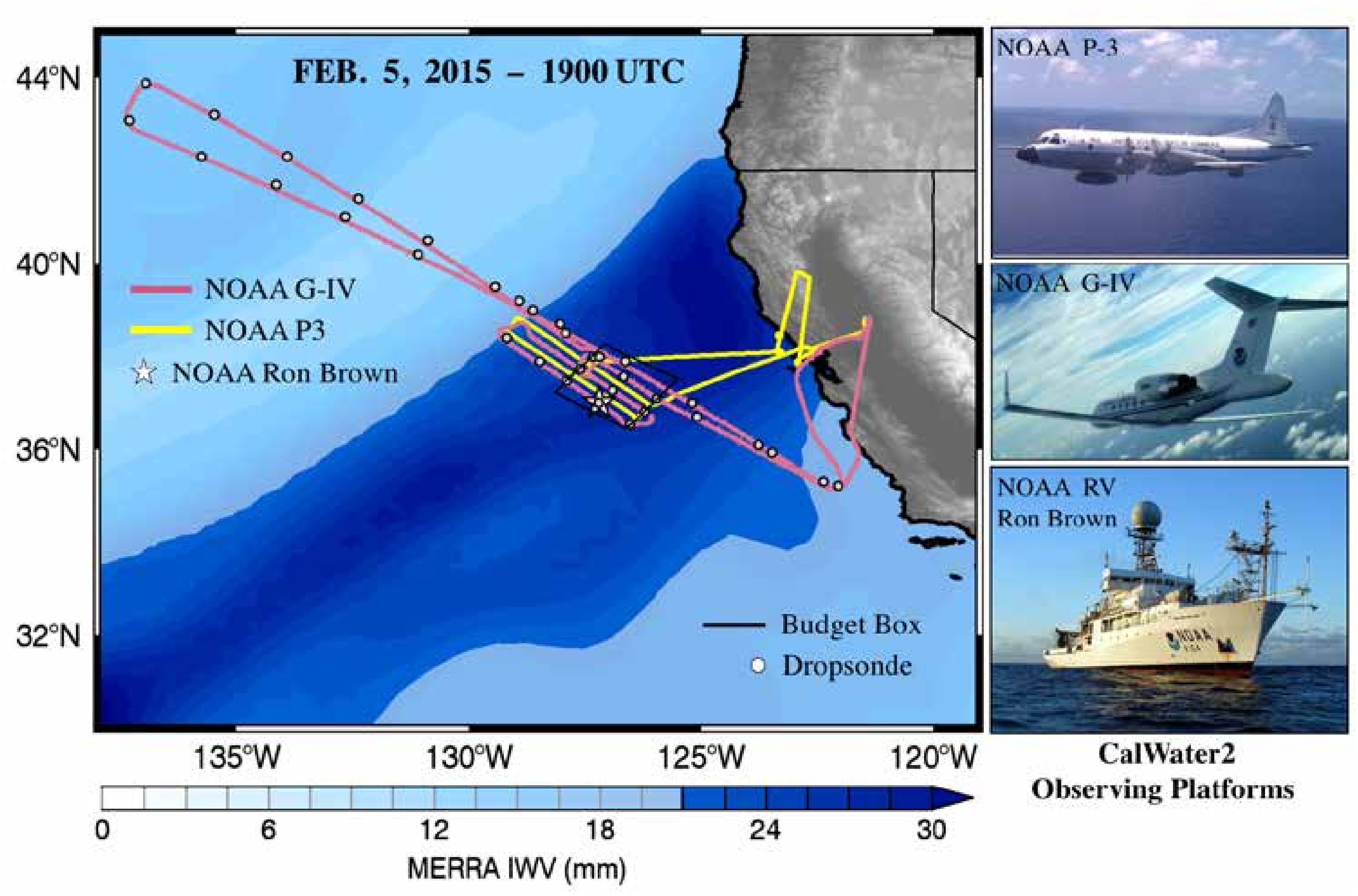

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Measured: z, p, T, RH, ***V***

Derived: mass flux, moisture flux, IWV

Satellite (SSMIS)

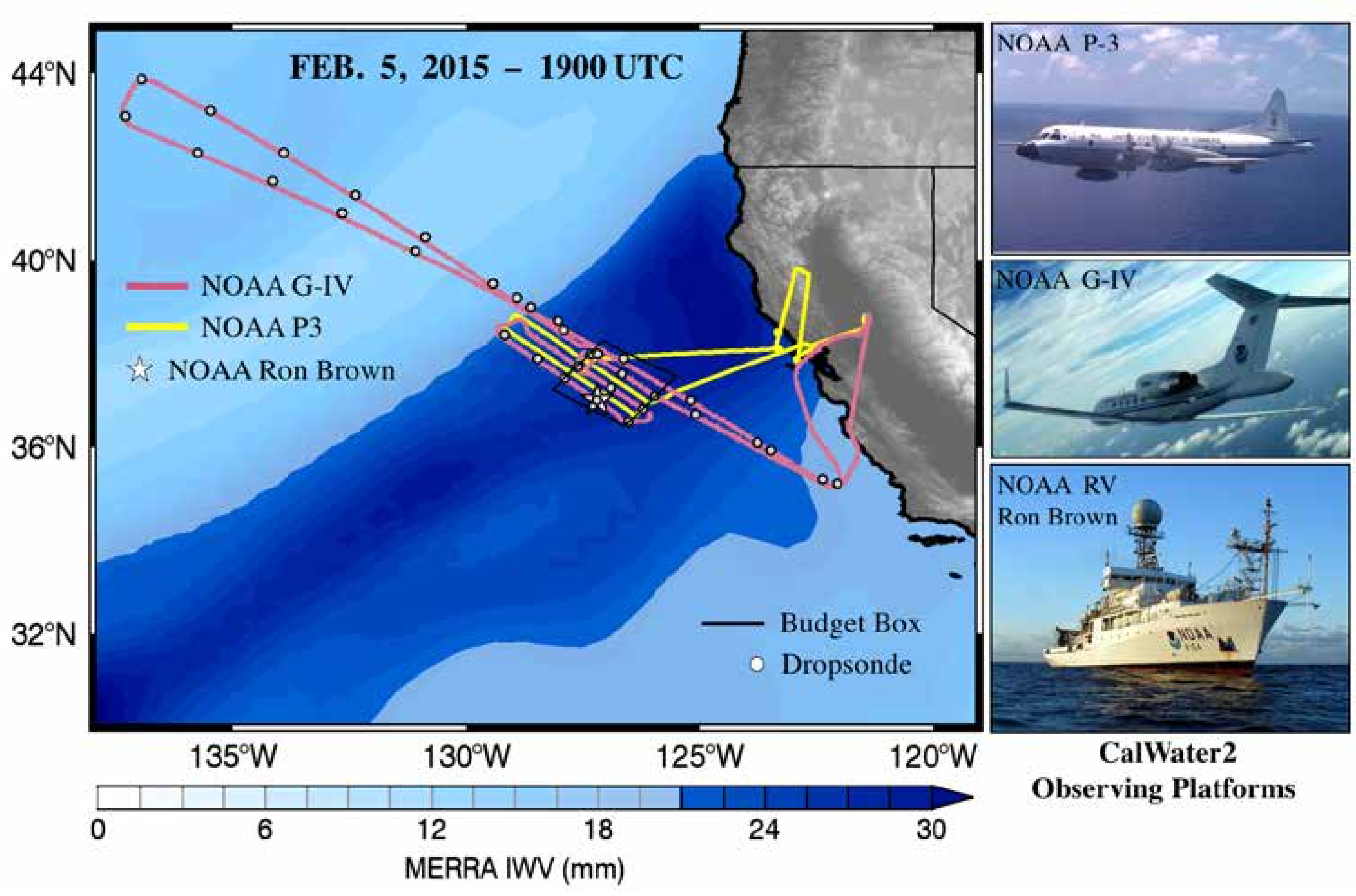
Retrieved: IWV, precipitation (only for pattern matching)

Ship

Measured: T, RH, ***V***

Derived: surface evaporation

CalWater2 Observations on 5 February 2015



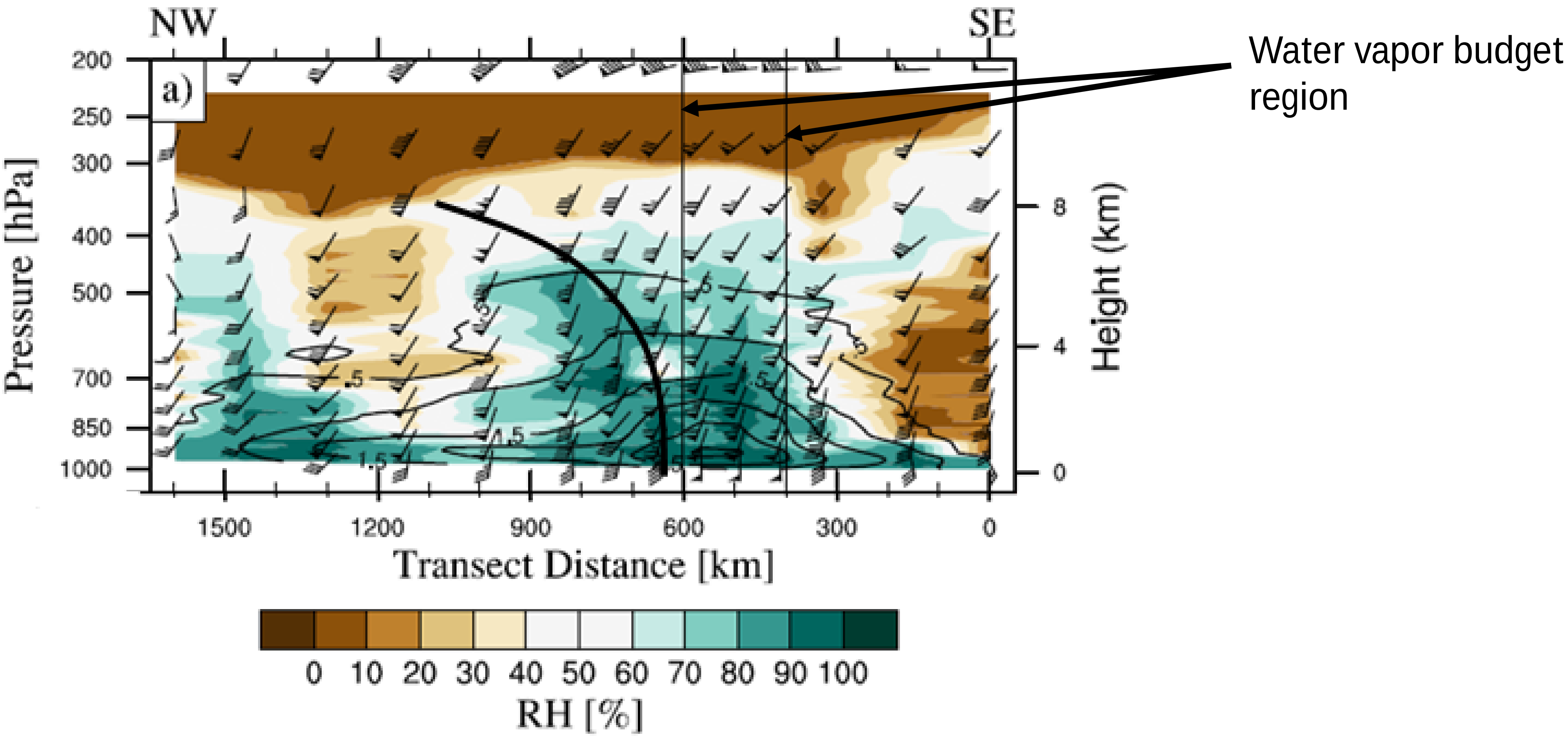
Dropsondes
Measured: z, p, T, RH, ***V***
Derived: mass flux, moisture flux, IWV

Satellite (SSMIS)
Retrieved: IWV, precipitation (only for pattern matching)

Ship
Measured: T, RH, ***V***, disdrometer
Derived: surface evaporation, Z-R relationship

Radar
Measured: reflectivity factor
Derived: precipitation

Dropsonde X-Section (*V*, RH, vapor flux)



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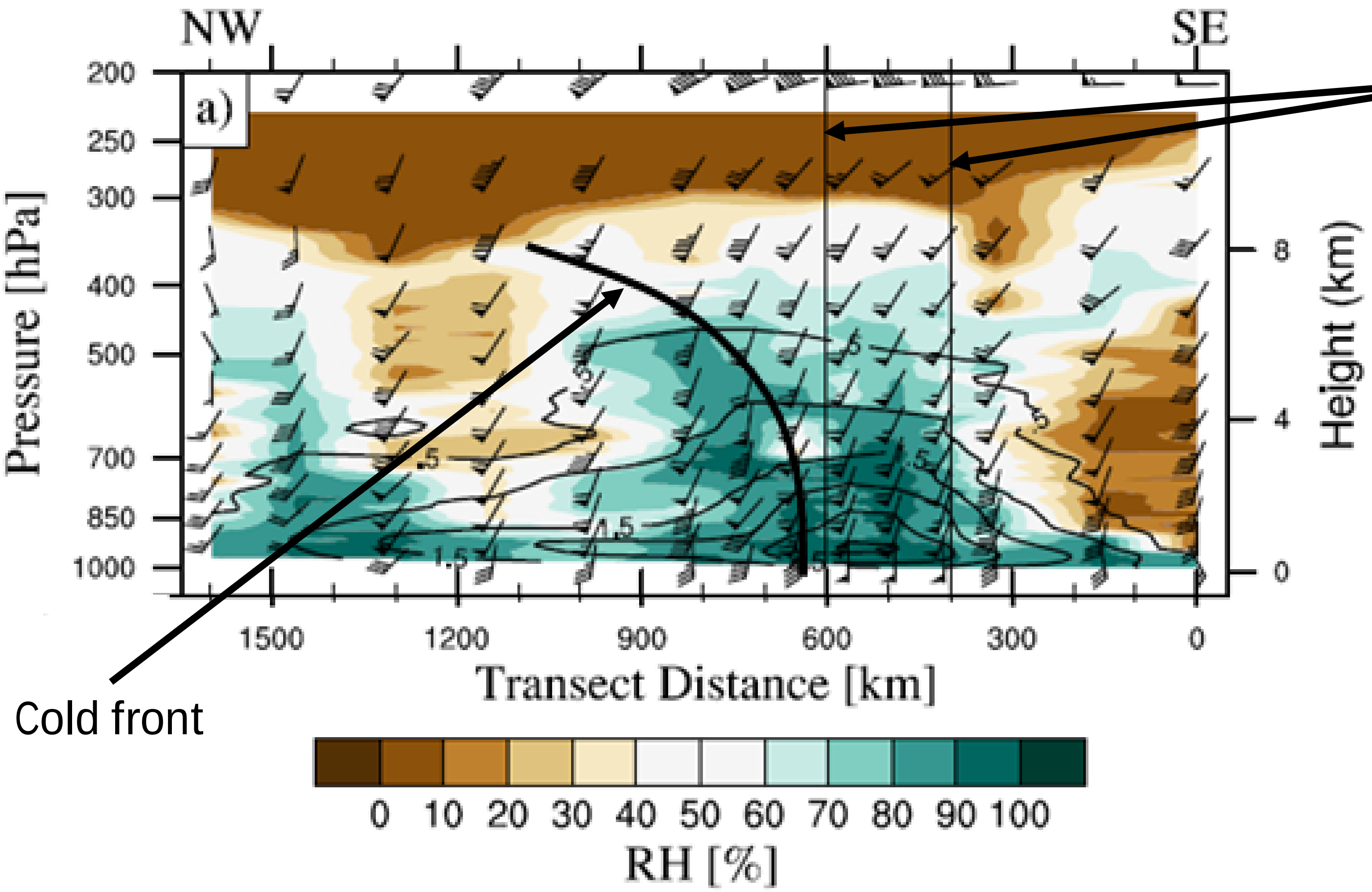
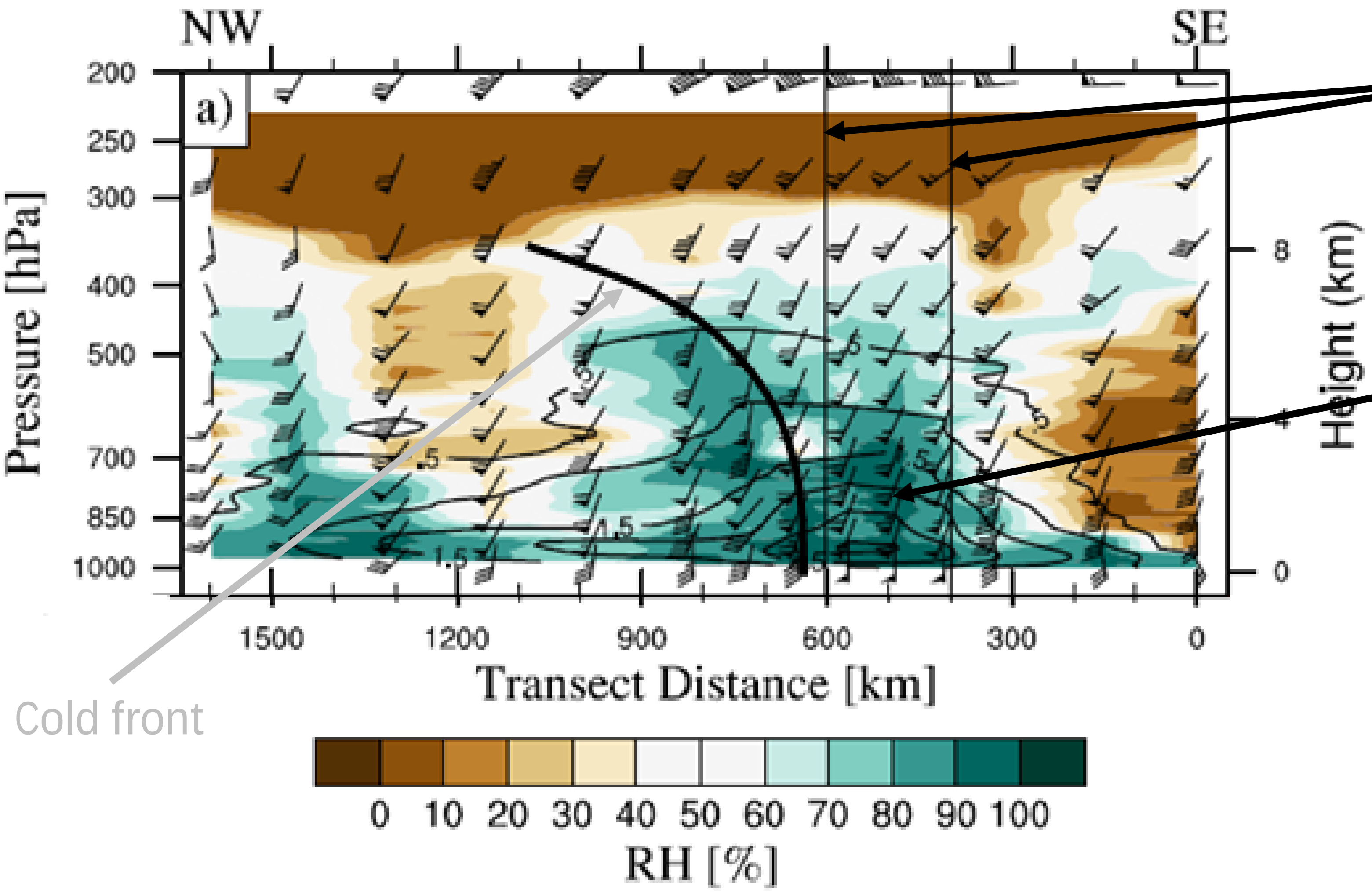


Water vapor budget region

Ahead of surface cold front

Cold front

Dropsonde X-Section (*V*, RH, vapor flux)



Water vapor budget region

Ahead of surface cold front

Nearly saturated in lower troposphere

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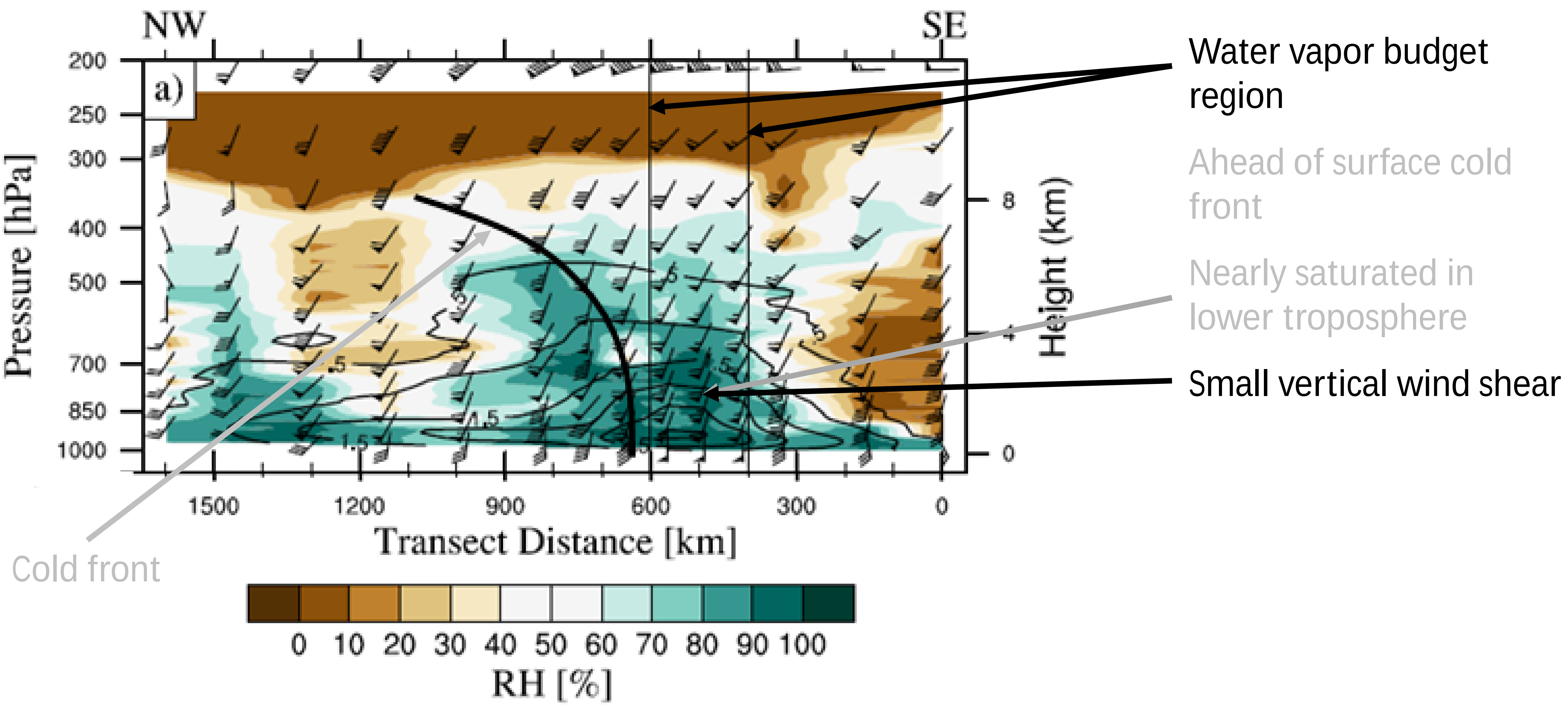

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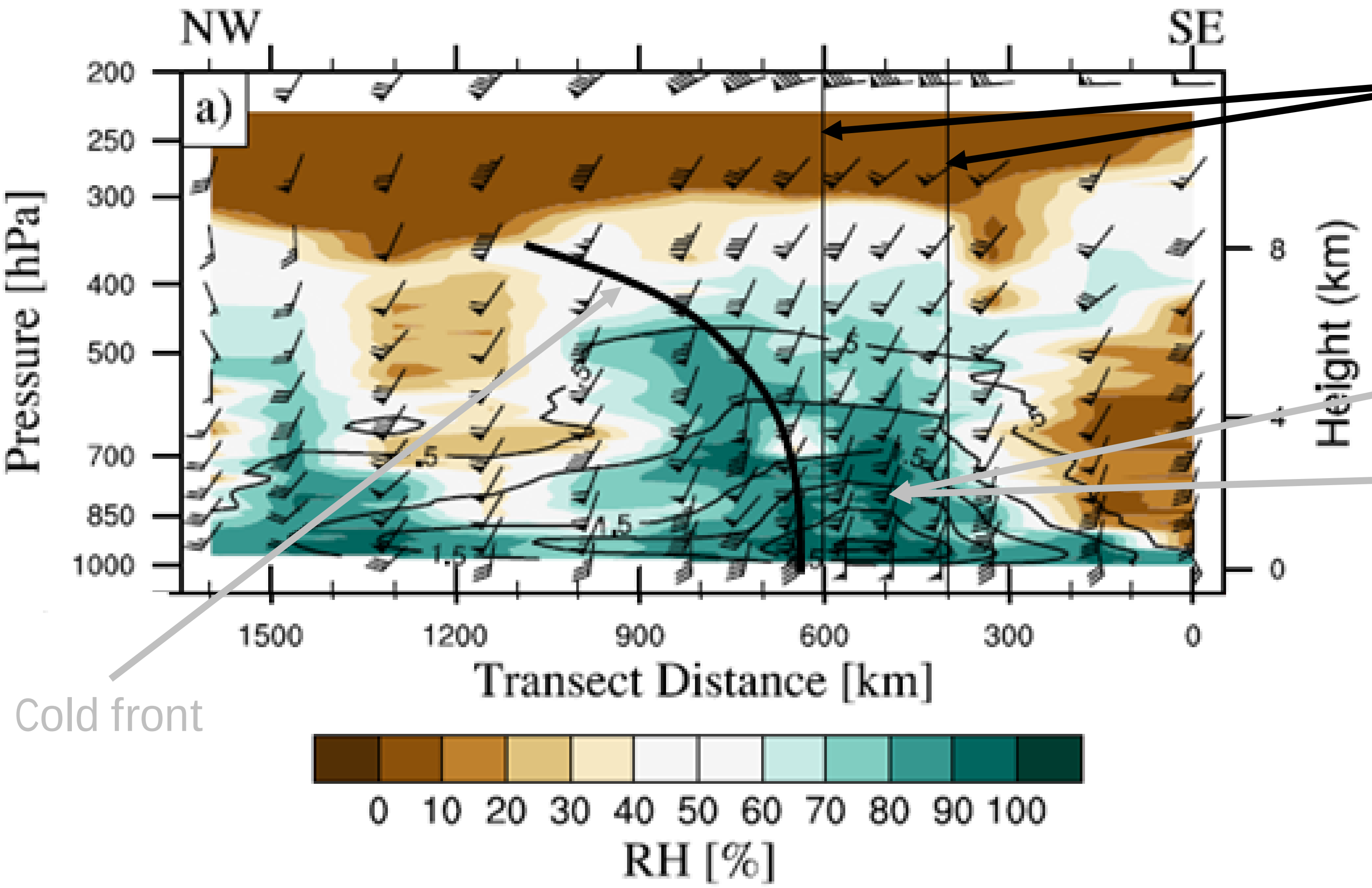


Water vapor budget region

Ahead of surface cold front

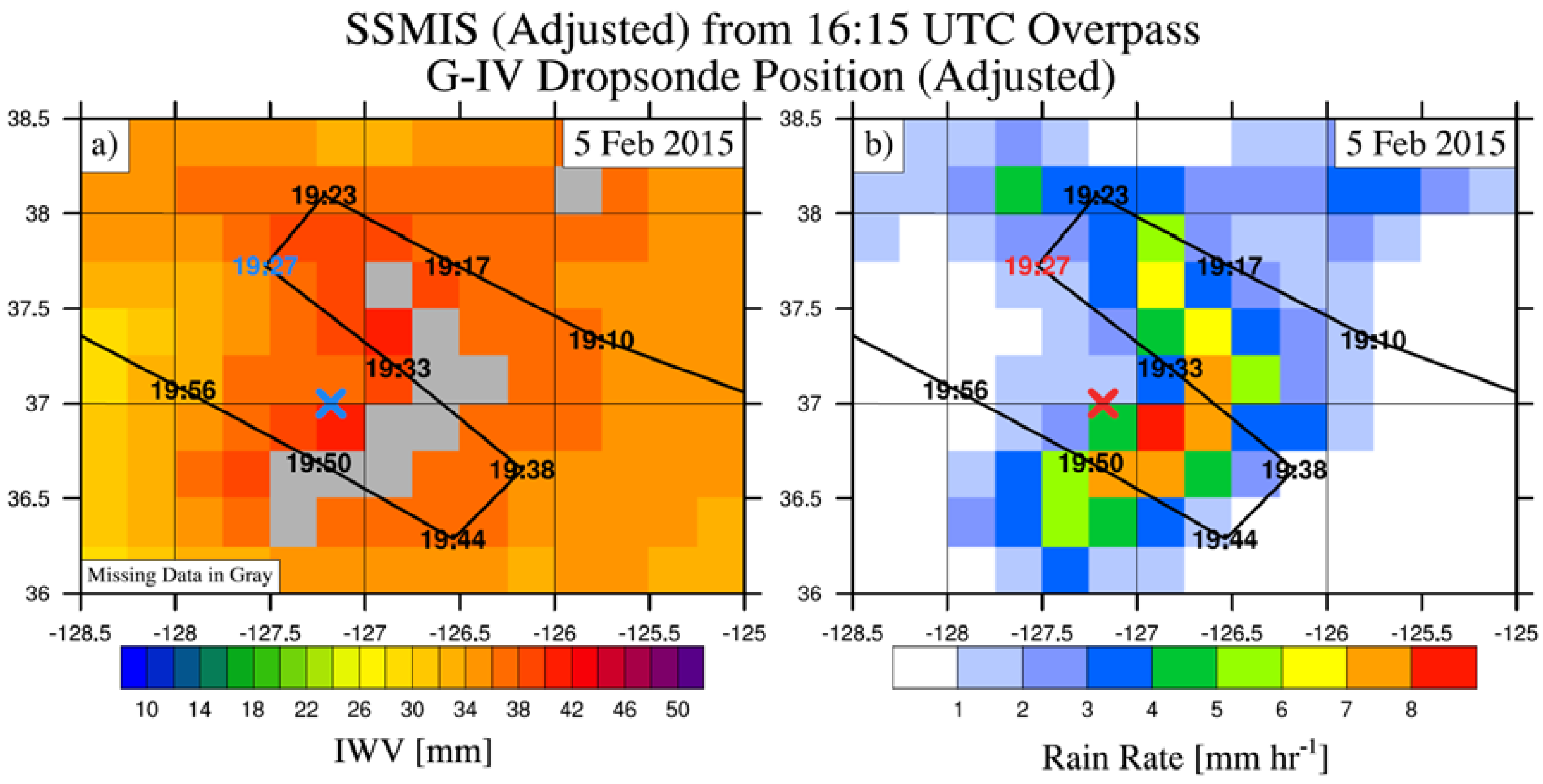
Nearly saturated in lower troposphere

Small vertical wind shear

Max water vapor flux is 3.2 kg s^{-1} m^{-1} hPa^{-1}

Max low-level wind is 32.5 m s^{-1}

Budget Region Dropsonde Times & Positions



Release time displayed (no usable data for 19:27)

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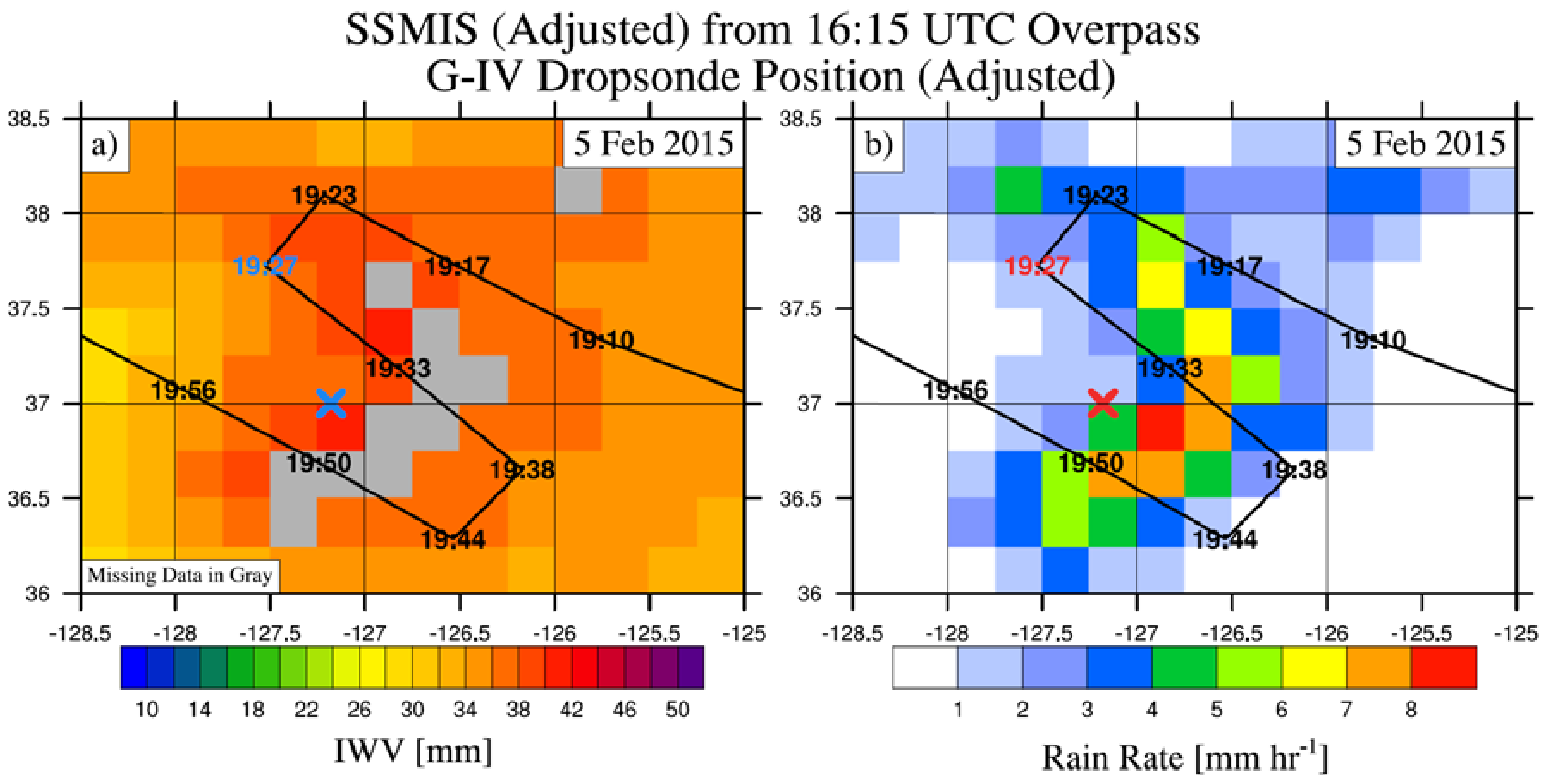

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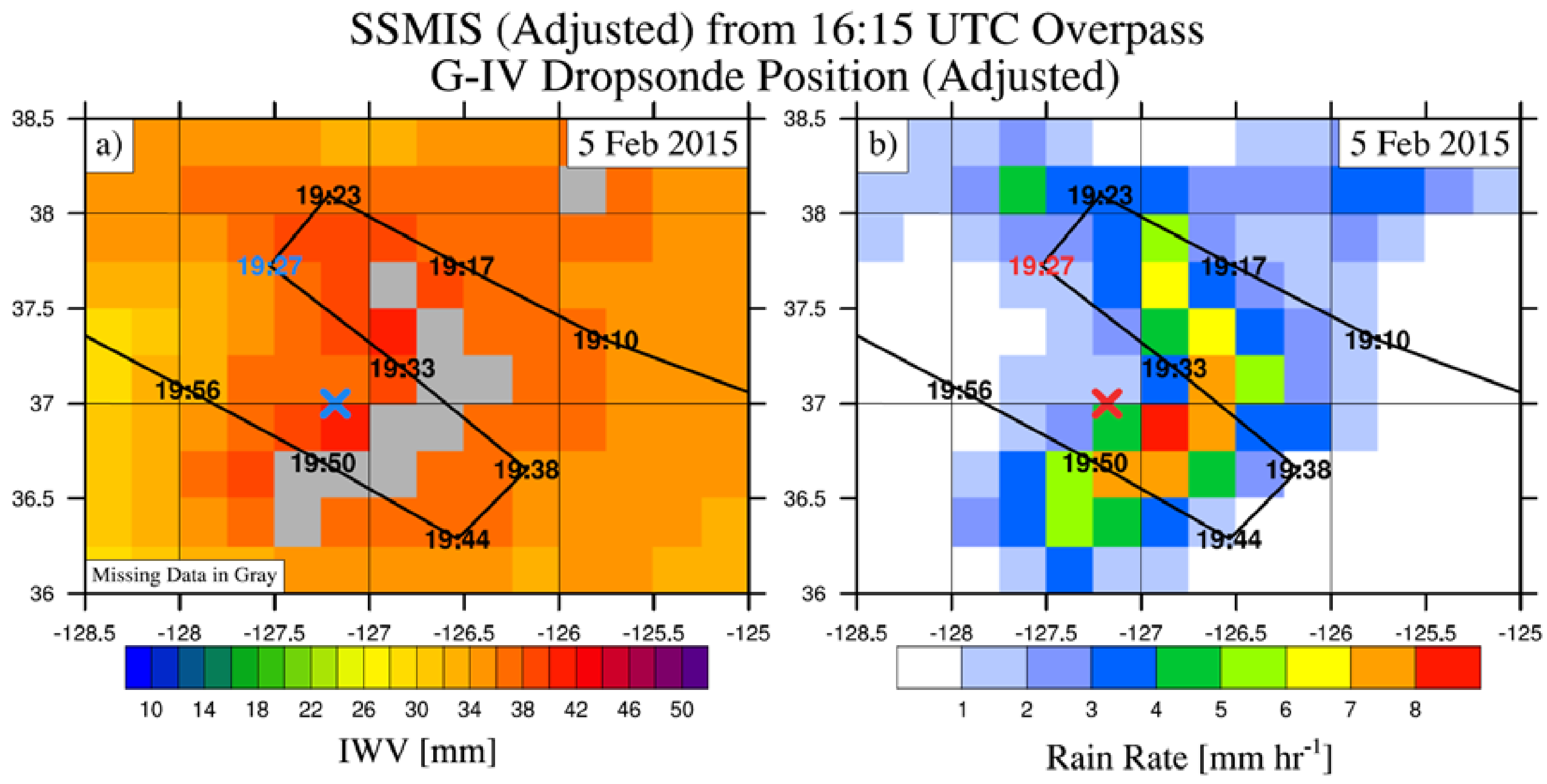
Surface position time-to-space adjusted by average wind to location at reference time of 19:30 UTC

Budget Region Dropsonde Times & Positions



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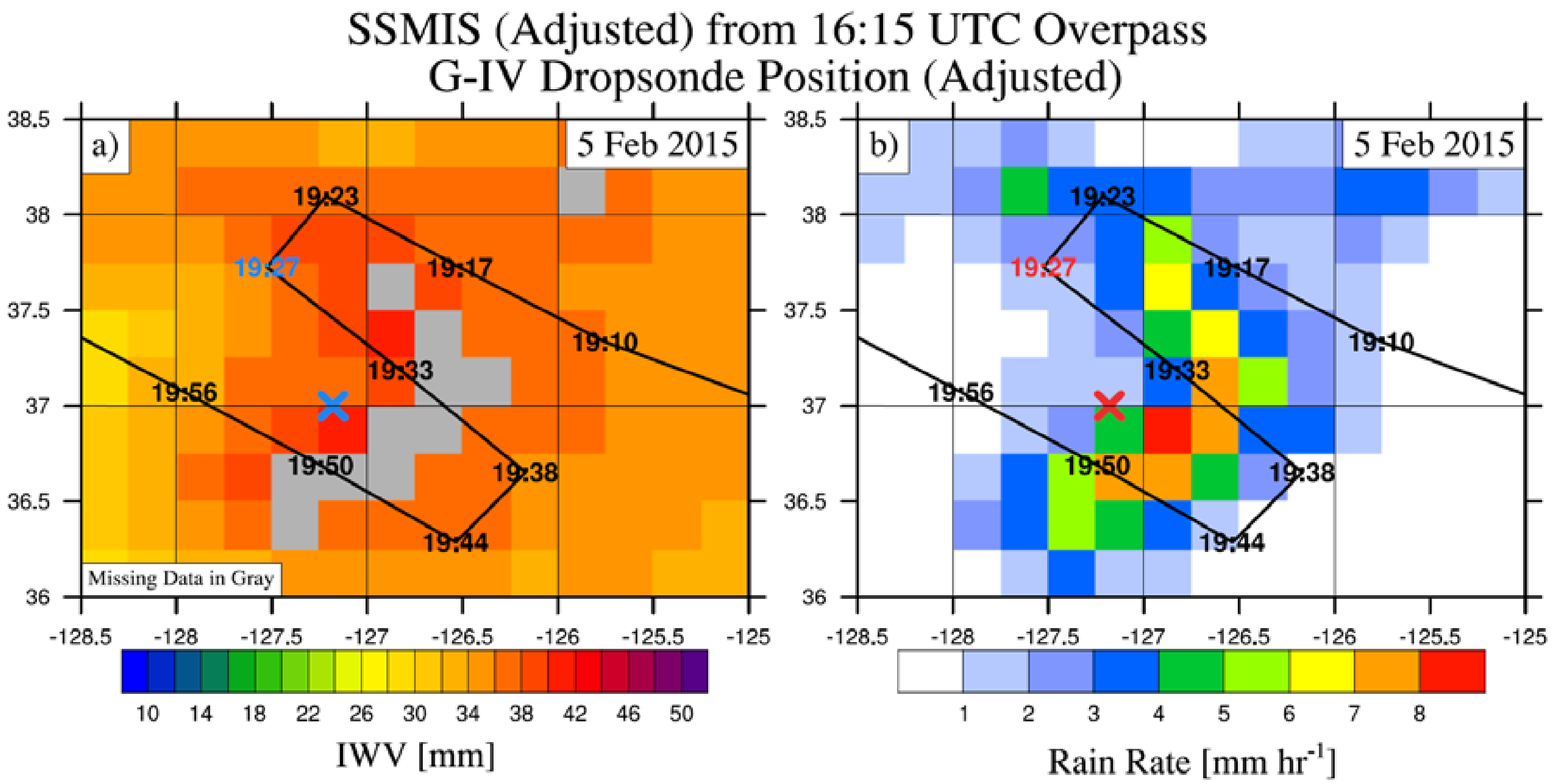
Surface position time-to-space adjusted by wind to location at reference time of 19:30 UTC

X marks ship position

Budget Region Dropsonde Times & Positions



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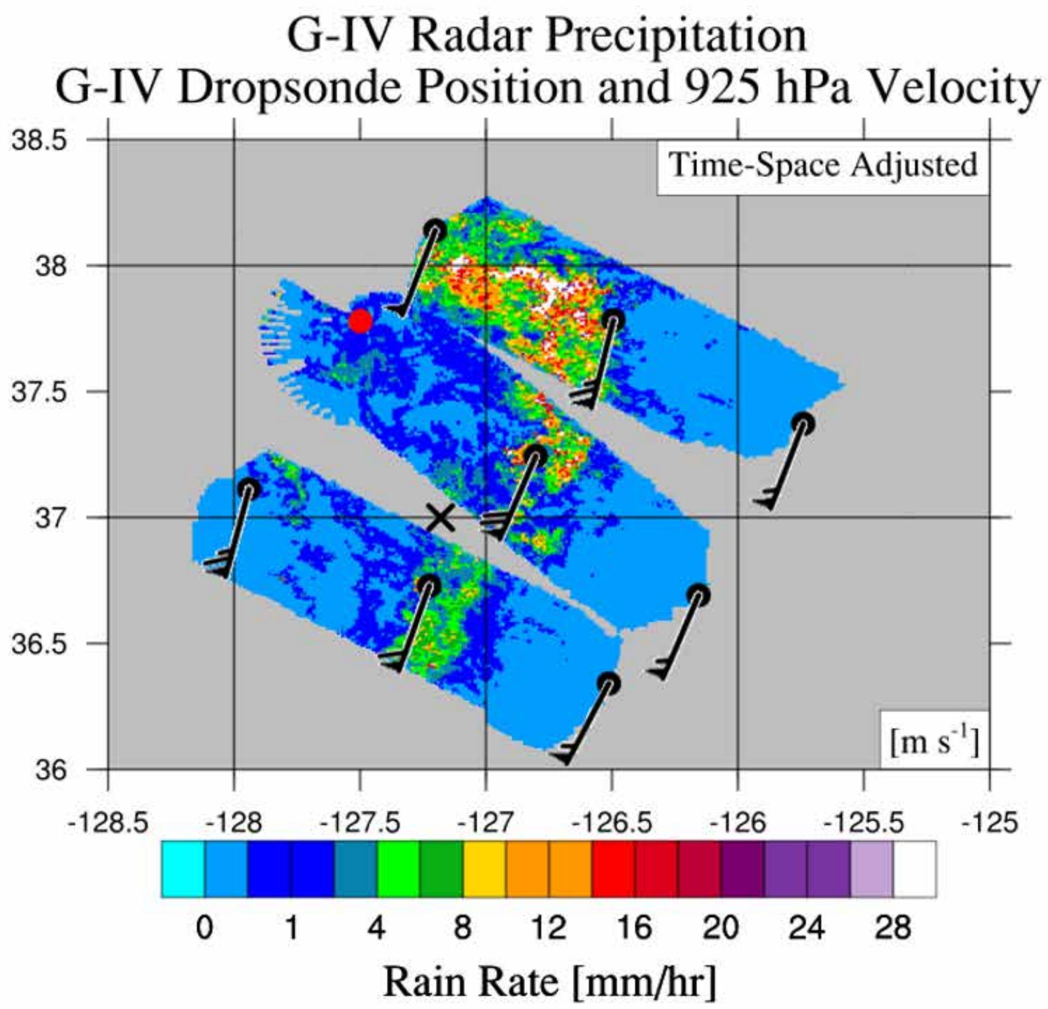
Surface position time-to-space adjusted by wind to location at reference time of 19:30 UTC

X marks ship position

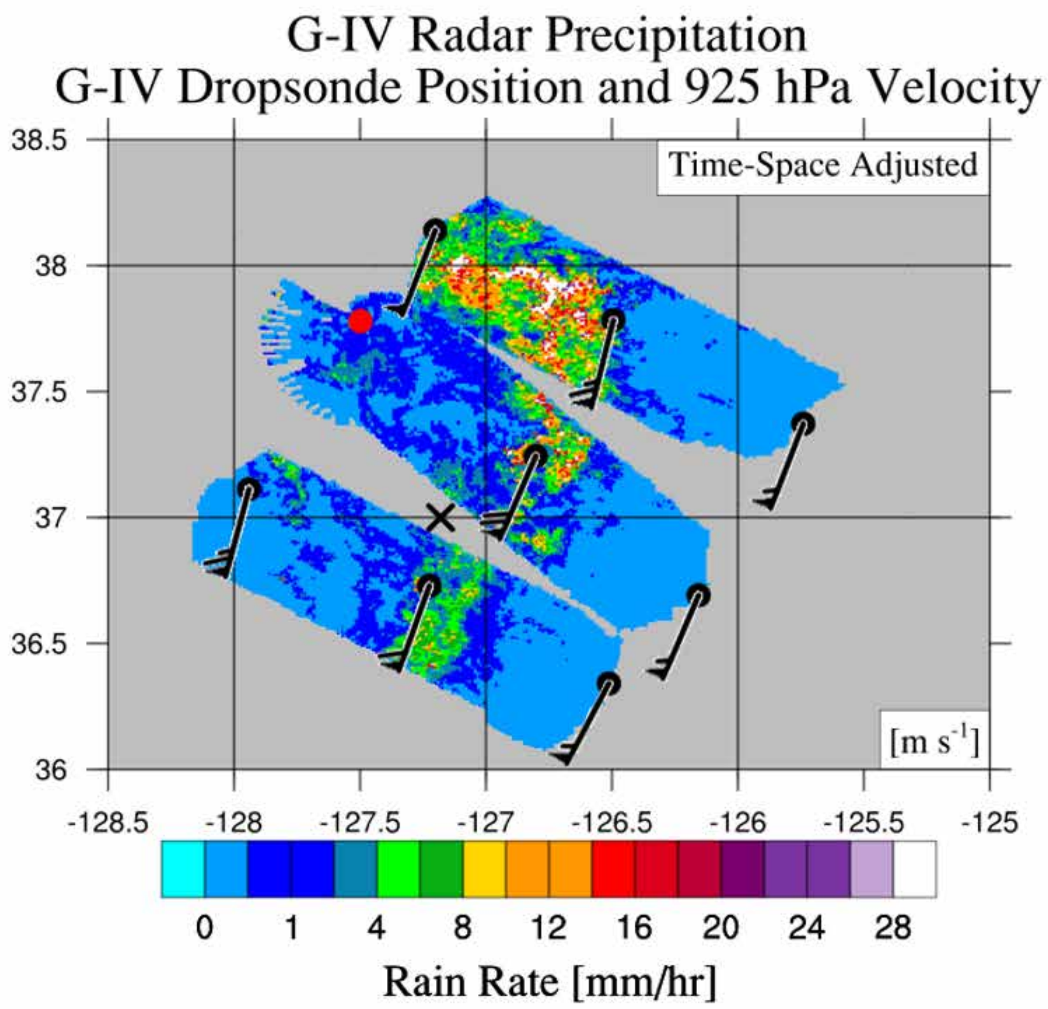
Satellite data from 3 h earlier time-to-space adjusted by matching precipitation pattern

Budget Region Radar-Estimated Precipitation



Radar-estimated rain rate at 1-1.5 km MSL after time-to-space adjustment to location at reference time of 19:30 UTC

Budget Region Radar-Estimated Precipitation



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Wind barbs indicate dropsonde 925 hPa wind

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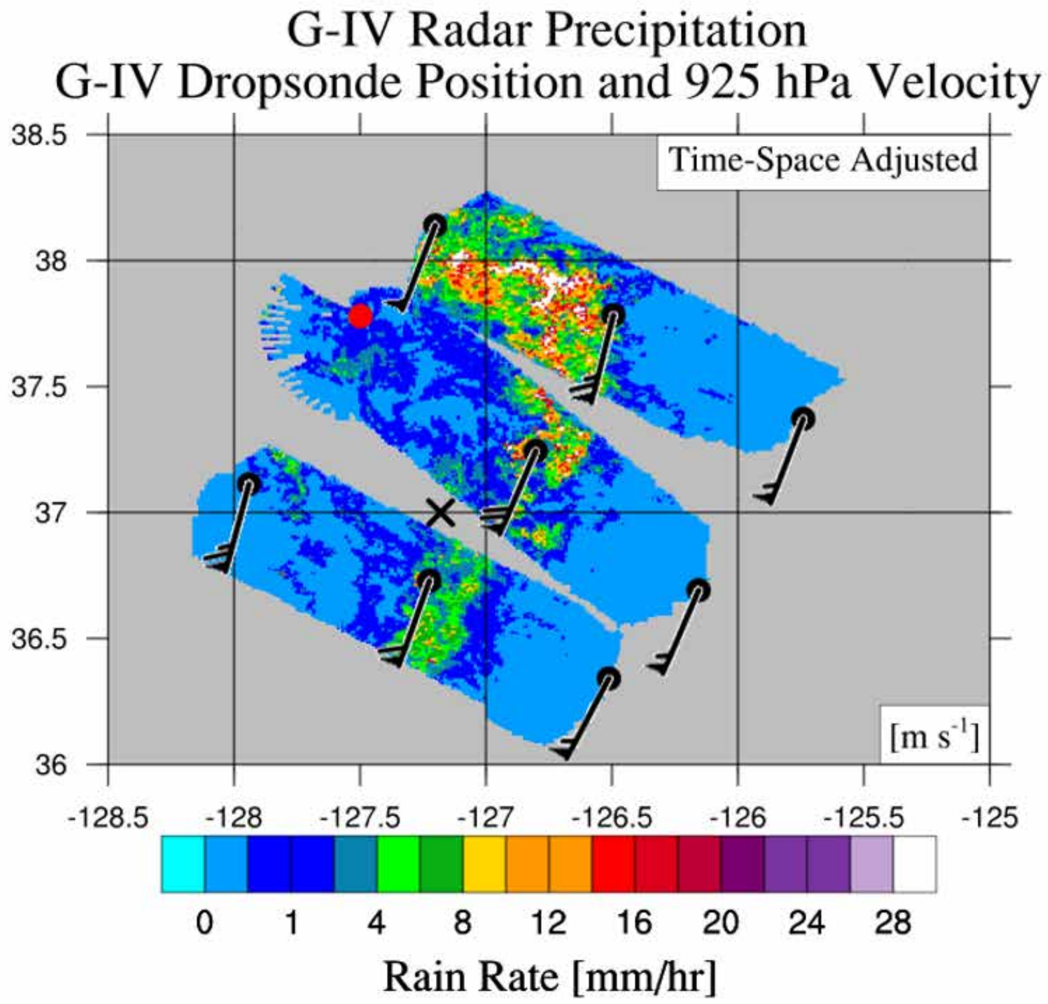

Radar-estimated rain rate at 1-1.5 km MSL after time-to-space adjustment to location at reference time of 19:30 UTC

Wind barbs indicate dropsonde 925 hPa wind

Dropsonde positions offset from radar swath center due to drift during time to descend to elevation measured by radar

Water Vapor Budget Terms

Surface w is assumed to be zero, and water condensate is neglected

$$\left.\frac{\partial IWV}{\partial t}\right|_{Eul}$$

IWV tendency in Eulerian reference frame

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$$\left.\frac{\partial IWV}{\partial t}\right|_{Eul} \approx \frac{1}{\rho_w}\left(\frac{1}{g}\int_0^{p_0} -\nabla \cdot (q\boldsymbol{V})\,dp \qquad\qquad\qquad\right)$$

IWV tendency in Eulerian reference frame »

Column Integrated Moisture Convergence (CIMC)

Water Vapor Budget Terms

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$$\left.\frac{\partial IWV}{\partial t}\right|_{Eul} \approx \frac{1}{\rho_w}\left(\frac{1}{g}\int_0^{p_0} -\nabla \cdot (q\boldsymbol{V})\,dp + E\right)$$

IWV tendency in Eulerian reference frame »

Column Integrated Moisture Convergence (CIMC) + Evaporation

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IWV tendency in Eulerian reference frame »

Column Integrated Moisture Convergence (CIMC) + Evaporation – Precipitation

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$$\frac{1}{g}\int_0^{p_0} -\nabla \cdot (q\boldsymbol{V})\, dp$$

Column Integrated Moisture Convergence (CIMC)

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Column Integrated Moisture Convergence (CIMC) + Evaporation – Precipitation

$$\frac{1}{g}\int_0^{p_0} -\nabla \cdot (q\boldsymbol{V})\, dp \approx \frac{1}{g}\int_0^{p_0} (-\boldsymbol{V} \cdot \nabla q)\, dp$$

Column Integrated Moisture Convergence (CIMC) »

Advection of Moisture (ADV)

Water Vapor Budget Terms

Surface w is assumed to be zero, and water condensate is neglected

$$\left.\frac{\partial IWV}{\partial t}\right|_{Eul} \approx \frac{1}{\rho_w}\left(\frac{1}{g}\int_0^{p_0} -\nabla \cdot (q\boldsymbol{V})\, dp + E - P\right)$$

IWV tendency in Eulerian reference frame »

Column Integrated Moisture Convergence (CIMC) + Evaporation – Precipitation

$$\frac{1}{g}\int_0^{p_0} -\nabla \cdot (q\boldsymbol{V})\, dp \approx \frac{1}{g}\int_0^{p_0} (-\boldsymbol{V} \cdot \nabla q)\, dp + \frac{1}{g}\int_0^{p_0} q(-\nabla \cdot \boldsymbol{V})\, dp$$

Column Integrated Moisture Convergence (CIMC) »

Advection of Moisture (ADV) + Dynamical Convergence of Moisture (CONV)

Water Vapor Budget Terms

Advection of Moisture (ADV) only moves a column of moisture from one place to another and does not result in precipitation.

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Dynamical Convergence of Moisture (CONV) is closely related to upward ascent of moisture and can therefore result in precipitation.

$$\frac{1}{g}\int_0^{p_0} q(-\nabla \cdot \boldsymbol{V})\, dp = \frac{1}{g}\int_0^{p_0} \left(-\omega \frac{\partial q}{\partial p}\right) dp$$

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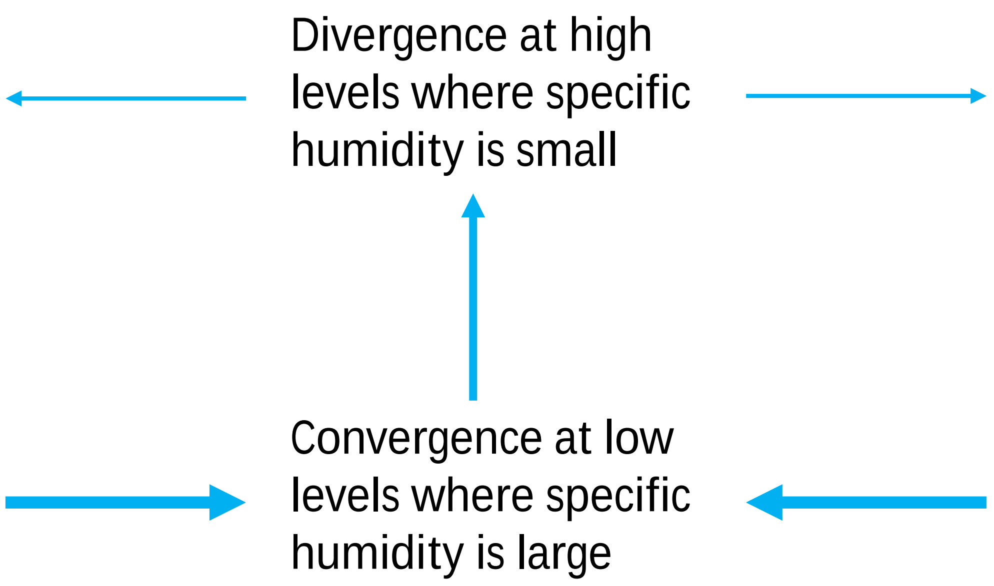


Water Vapor Budget Terms

$$\left.\frac{dIWV}{dt}\right|_{Lagr}$$

IWV tendency in Lagrangian reference frame

Water Vapor Budget Terms

$$\left.\frac{dIWV}{dt}\right|_{Lagr} = \left.\frac{\partial IWV}{\partial t}\right|_{Eul} - ADV$$

IWV tendency in Lagrangian reference frame =

IWV tendency in Eulerian reference frame – Advection of Moisture (ADV)

Water Vapor Budget Terms

$$\left.\frac{dIWV}{dt}\right|_{Lagr} = \left.\frac{\partial IWV}{\partial t}\right|_{Eul} - ADV \approx CONV$$

IWV tendency in Lagrangian reference frame =

IWV tendency in Eulerian reference frame – Advection of Moisture (ADV)

IWV tendency in Lagrangian reference frame »

Dynamical Convergence of Moisture (CONV)

Water Vapor Budget Terms

$$\left.\frac{dIWV}{dt}\right|_{Lagr} = \left.\frac{\partial IWV}{\partial t}\right|_{Eul} - ADV \approx CONV + E$$

IWV tendency in Lagrangian reference frame =

IWV tendency in Eulerian reference frame – Advection of Moisture (ADV)

IWV tendency in Lagrangian reference frame ≈

Dynamical Convergence of Moisture (CONV) + Evaporation

Water Vapor Budget Terms

$$\left.\frac{dIWV}{dt}\right|_{Lagr} = \left.\frac{\partial IWV}{\partial t}\right|_{Eul} - ADV \gg CONV + E - P$$

IWV tendency in Lagrangian reference frame =

IWV tendency in Eulerian reference frame – Advection of Moisture (ADV)

IWV tendency in Lagrangian reference frame »

Dynamical Convergence of Moisture (CONV) + Evaporation – Precipitation

Water Vapor Budget Terms

$$\left.\frac{dIWV}{dt}\right|_{Lagr} = \left.\frac{\partial IWV}{\partial t}\right|_{Eul} - ADV \approx CONV + E - P$$

IWV tendency in Lagrangian reference frame =

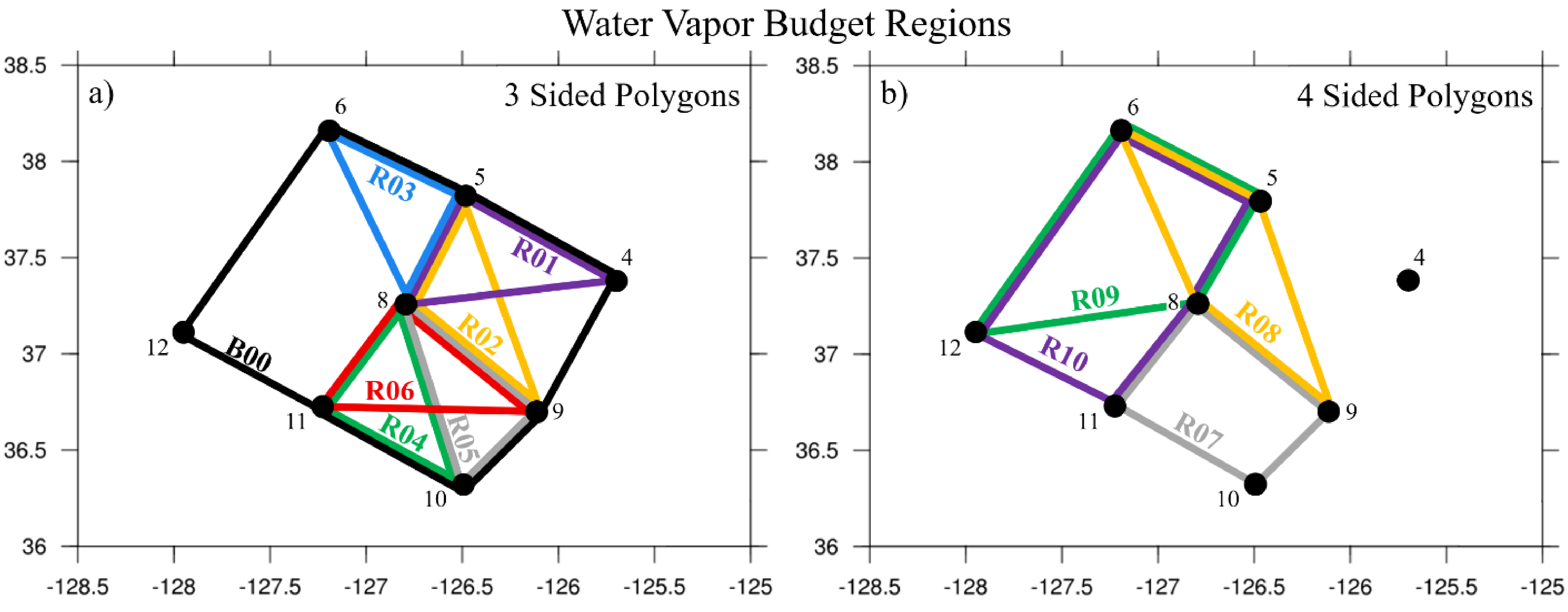
IWV tendency in Eulerian reference frame – Advection of Moisture (ADV)

IWV tendency in Lagrangian reference frame ≈

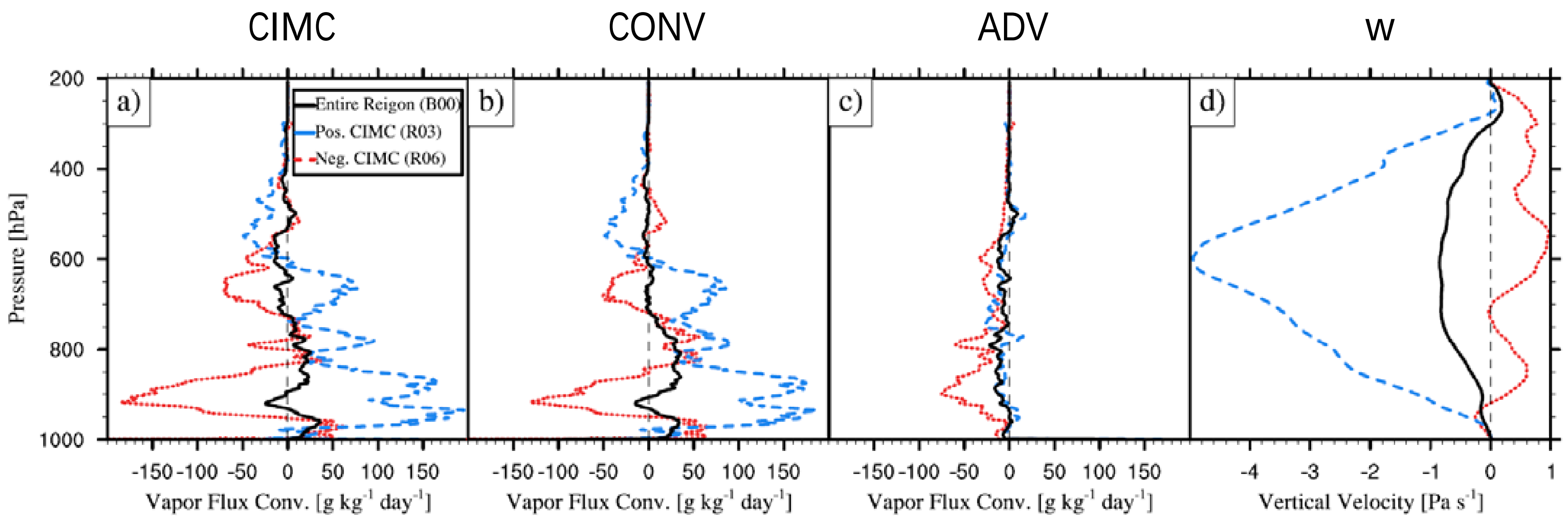
Dynamical Convergence of Moisture (CONV) + Evaporation – Precipitation

The Lagrangian reference frame is most relevant for investigating physical processes adding or removing moisture from a moving atmospheric column

Water Vapor Budget Regions

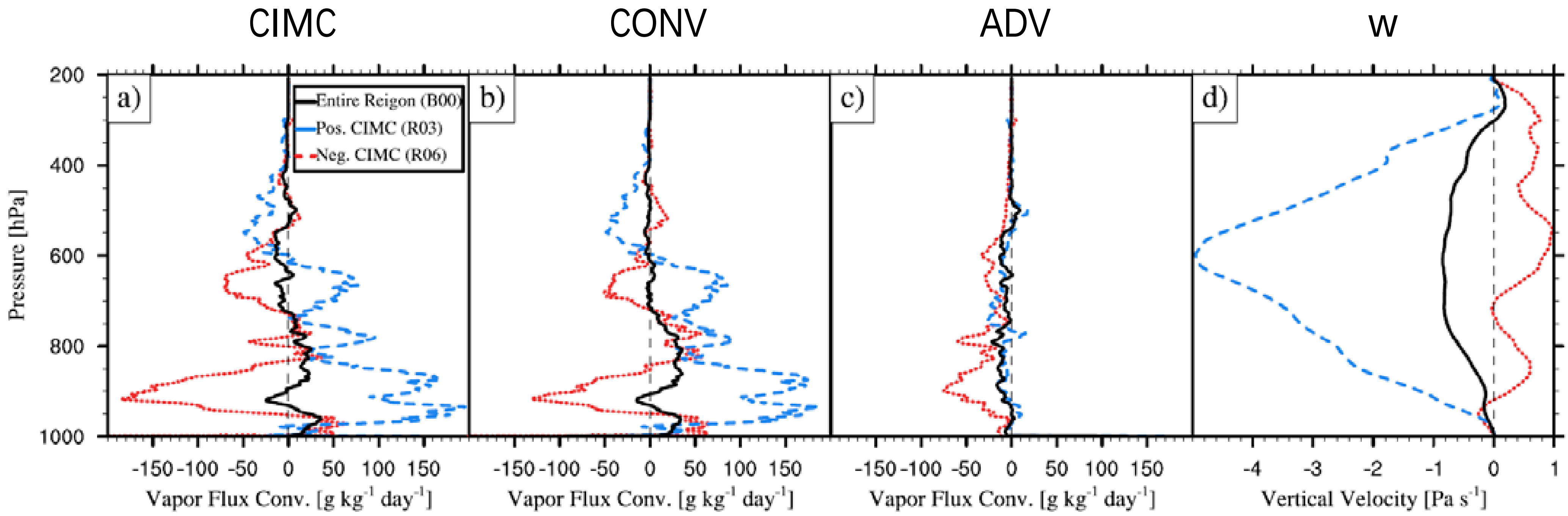


Substantial Variability among Subregions



Subregion with most positive CIMC has strong upward motion and low-level dynamical convergence

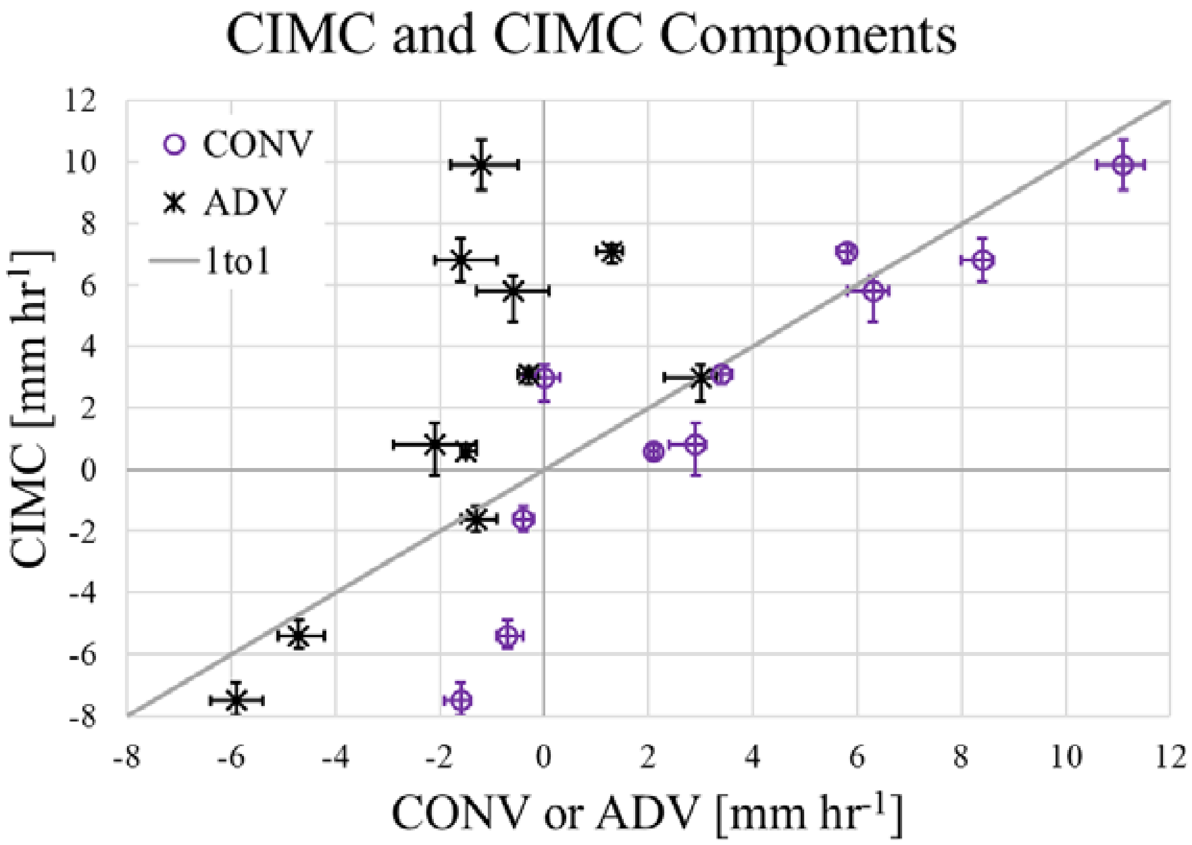
Substantial Variability among Subregions



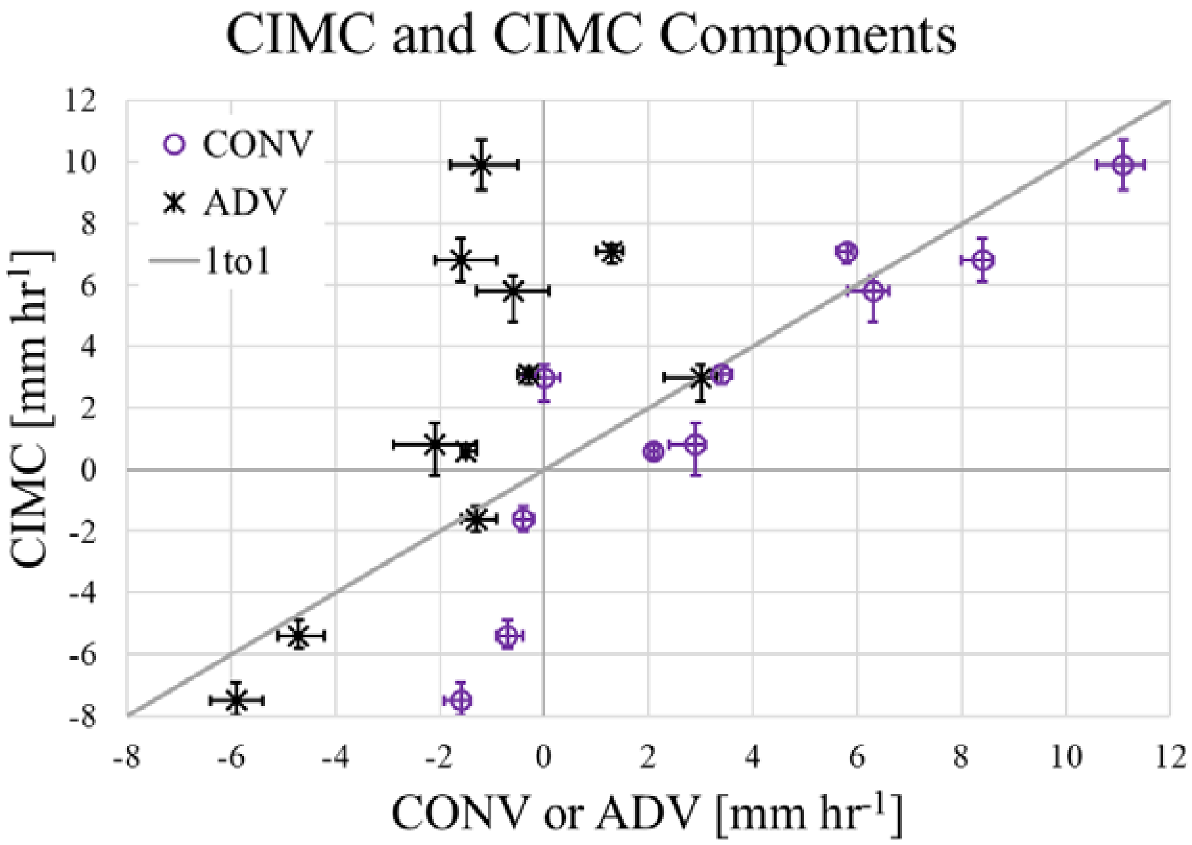
Subregion with most positive CIMC has strong upward motion and low-level dynamical convergence

Subregion with most negative CIMC has downward motion, low-level dynamical divergence, and advective drying

Contributions of ADV and CONV to CIMC



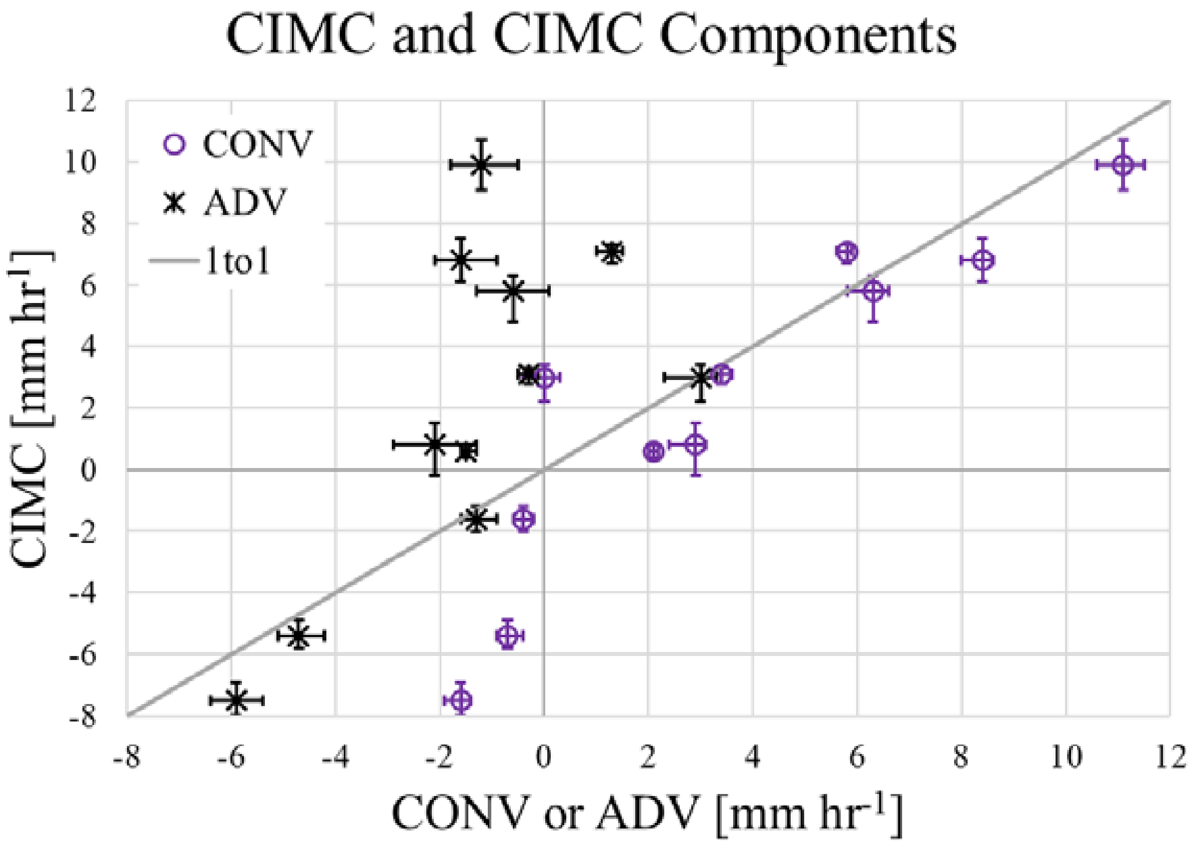
Contributions of ADV and CONV to CIMC



Among subregions…

- Large positive column integrated moisture convergence results primarily from dynamical convergence of moisture

Contributions of ADV and CONV to CIMC



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  - *Low-level convergence is favored in this synoptic environment*

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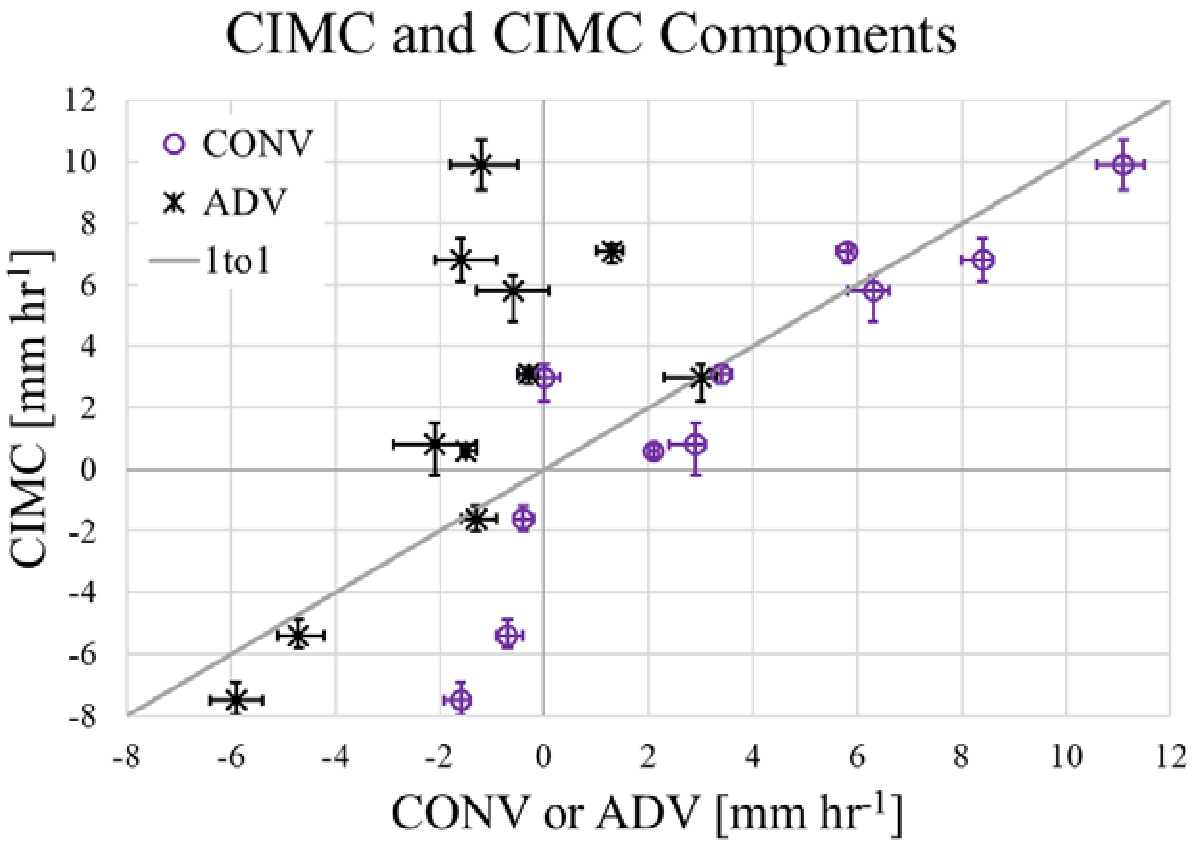

Among subregions…

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- Large negative in column integrated moisture convergence results primarily from advective drying

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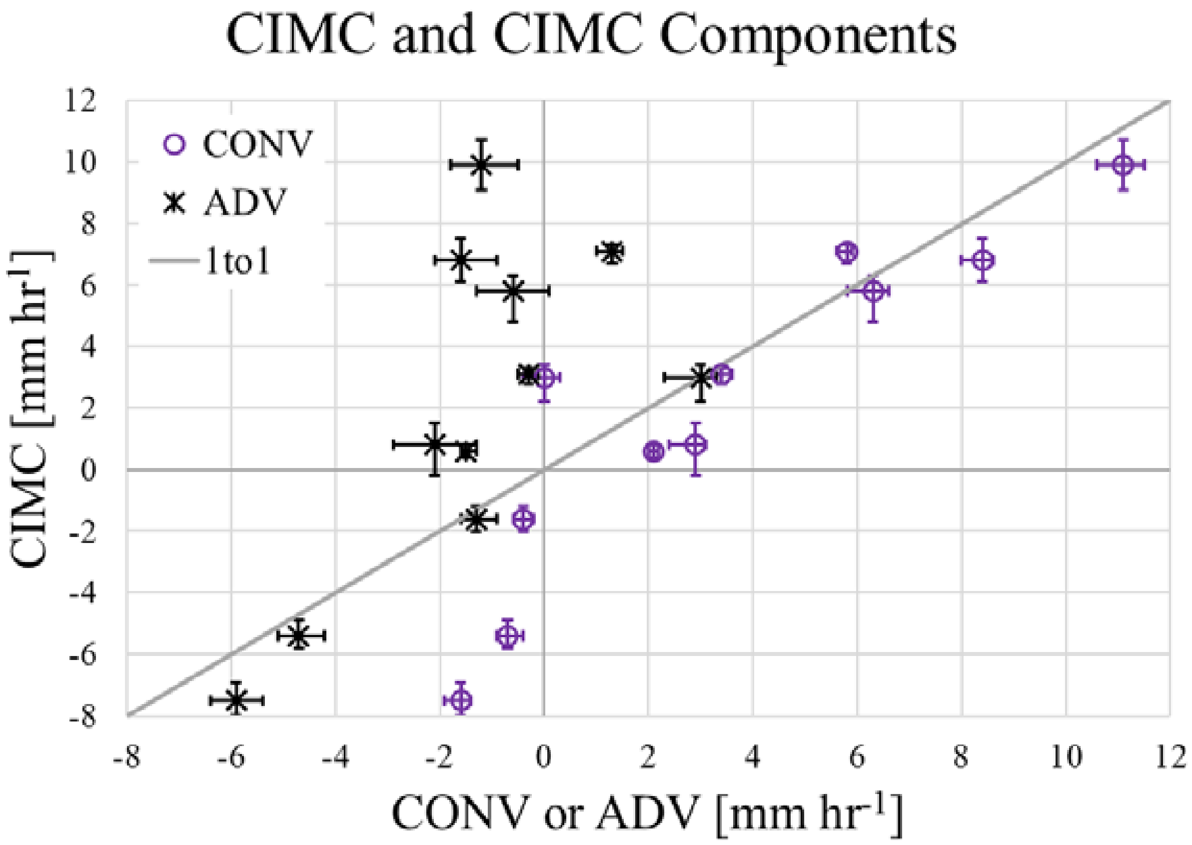
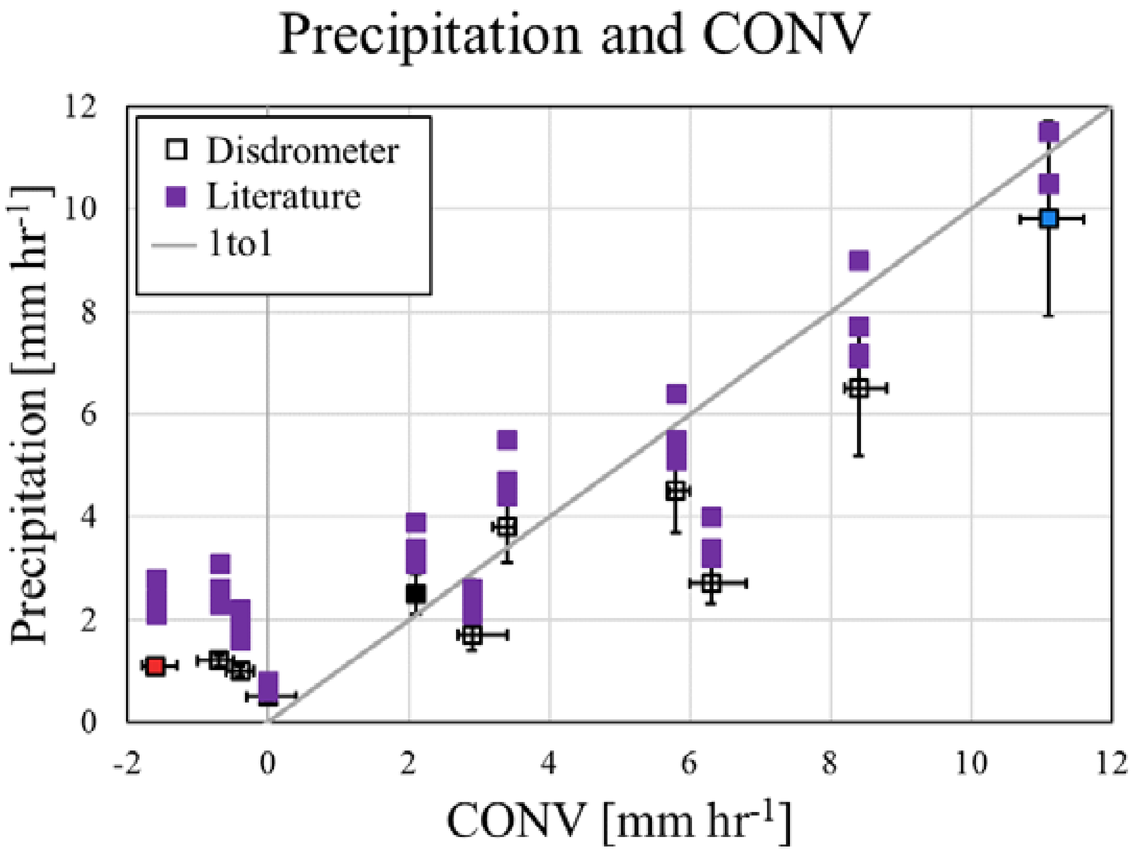


Among subregions…

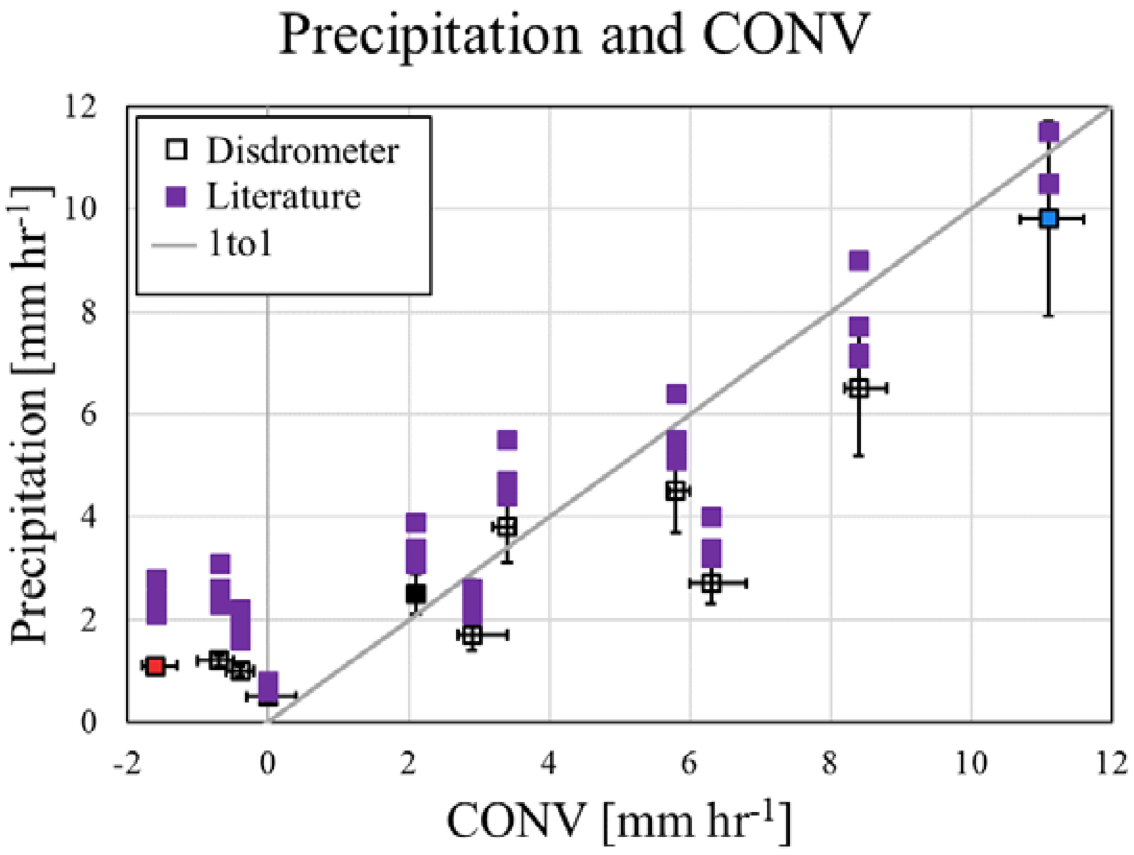
- Large positive column integrated moisture convergence results primarily from dynamical convergence of moisture
  - *Low-level convergence is favored in this synoptic environment*
- Large negative in column integrated moisture convergence results primarily from advective drying
  - *This is the moistest area of the AR, so advection can only bring in drier air*

CONV and Precipitation



Boxes with error bars use a Z-R relationship empirically derived from ship disdrometer

CONV and Precipitation



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Purple boxes use previously published Z-R relationships not derived for oceanic AR conditions

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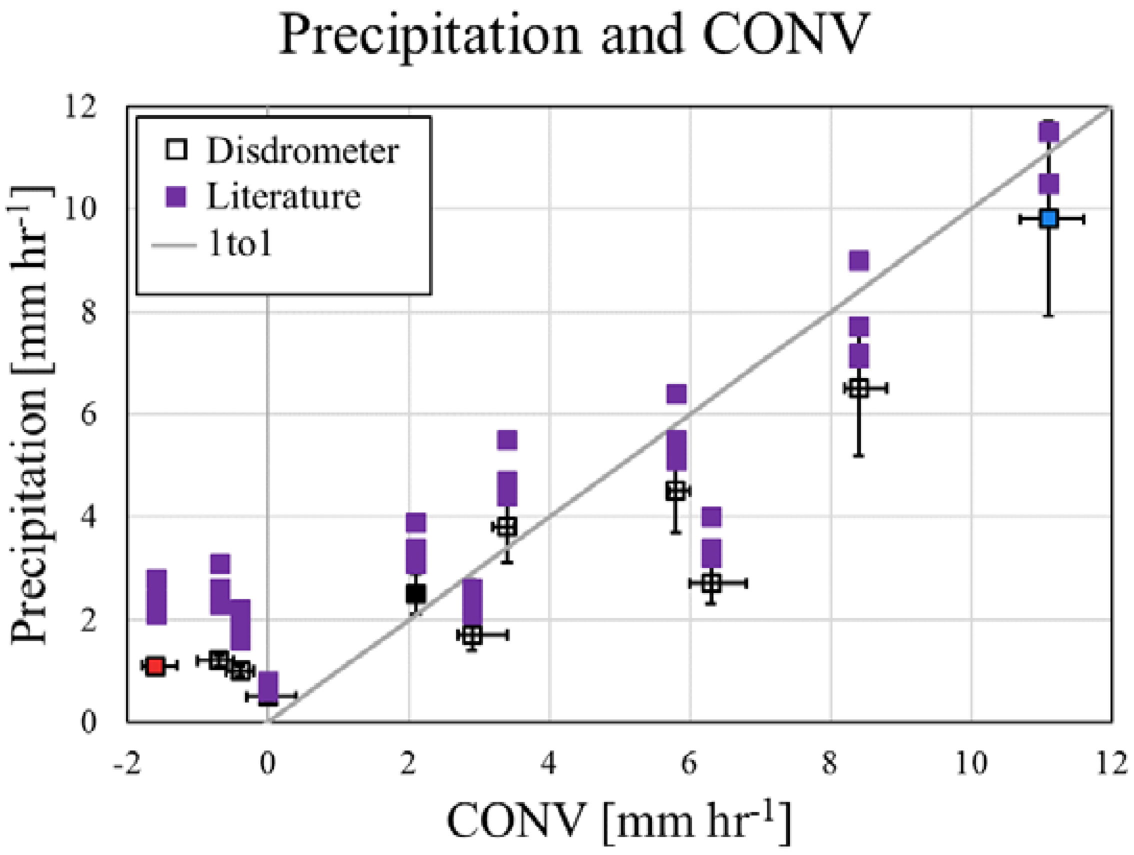

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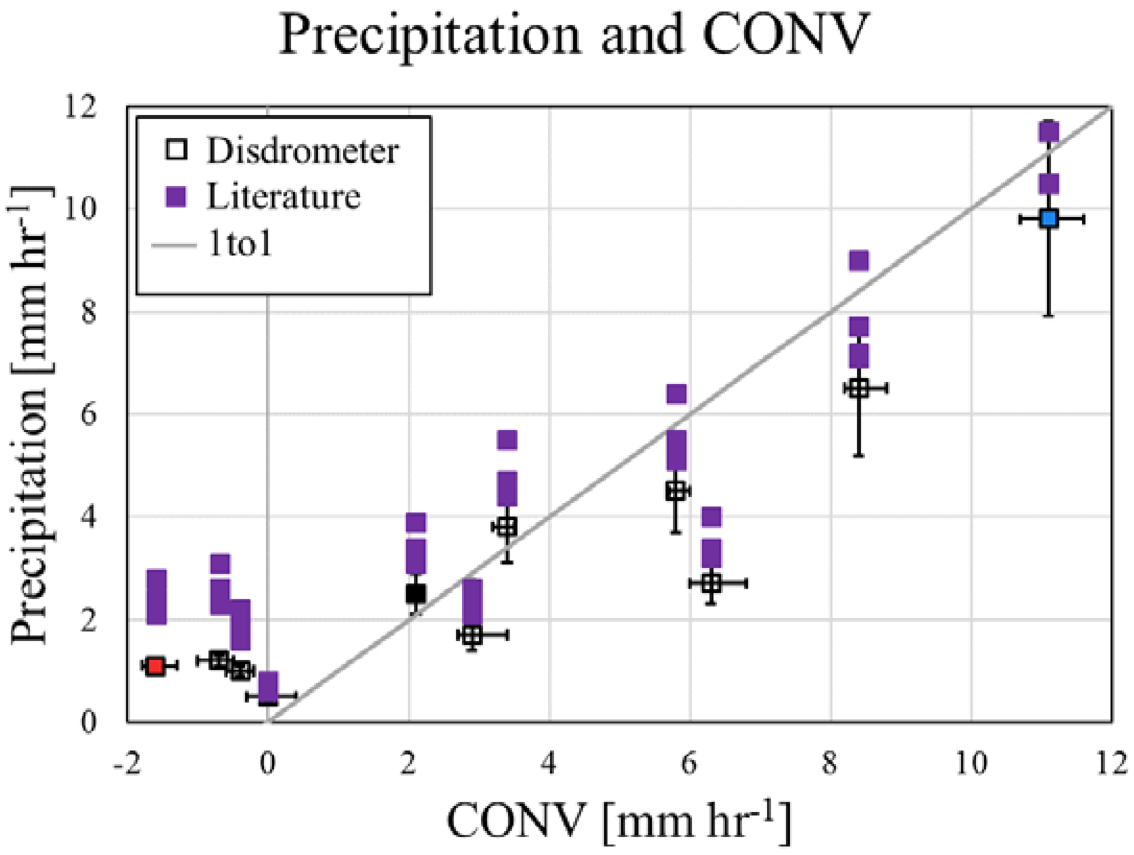
Among subregions…

- Precipitation rate increases proportionally to positive dynamical convergence of moisture

CONV and Precipitation



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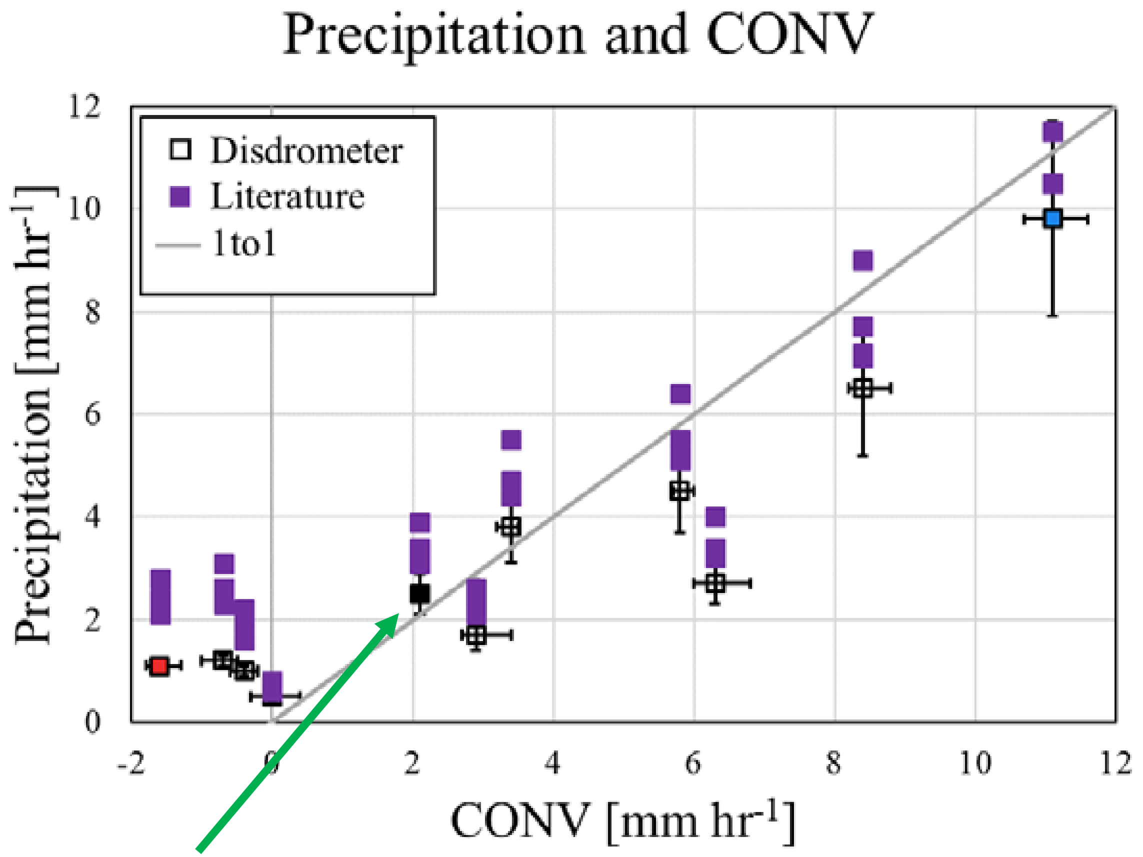
Among subregions…

- Precipitation rate increases proportionally to positive dynamical convergence of moisture
- The increase in column moisture from dynamical convergence is mostly removed by precipitation

CONV and Precipitation



entire budget region

Boxes with error bars use a Z-R relationship empirically derived from ship disdrometer

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Among subregions...

- Precipitation rate increases proportionally to positive dynamical convergence of moisture
- The increase in column moisture from dynamical convergence is mostly removed by precipitation

IWV Time Tendency

Instantaneous $\left.\frac{\partial IWV}{\partial t}\right|_{Eul} \approx ADV + CONV + E - P$

Instantaneous $\left.\frac{dIWV}{dt}\right|_{Lagr} \approx CONV + E - P$

IWV Time Tendency

Instantaneous $\left.\frac{\partial IWV}{\partial t}\right|_{Eul}$ » $ADV + CONV + E - P$

Instantaneous $\left.\frac{dIWV}{dt}\right|_{Lagr}$ » $CONV + E - P$

Time Difference $\left.\frac{\partial IWV}{\partial t}\right|_{Eul}$ = (Dropsonde IWV – SSMIS IWV_{Eul}) / 3.25 hr

Time Difference $\left.\frac{\partial IWV}{\partial t}\right|_{Lagr}$ = (Dropsonde IWV – SSMIS IWV_{Lagr}) / 3.25 hr

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Satellite IWV at budget region but 3.25 h earlier than dropsonde

Time Difference $\left.\frac{\partial IWV}{\partial t}\right|_{Eul}$ = (Dropsonde IWV – SSMIS IWV_{Eul}) / 3.25 hr

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Satellite IWV at location where budget column was 3.25 h earlier

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Satellite IWV at location where budget column was 3.25 h earlier

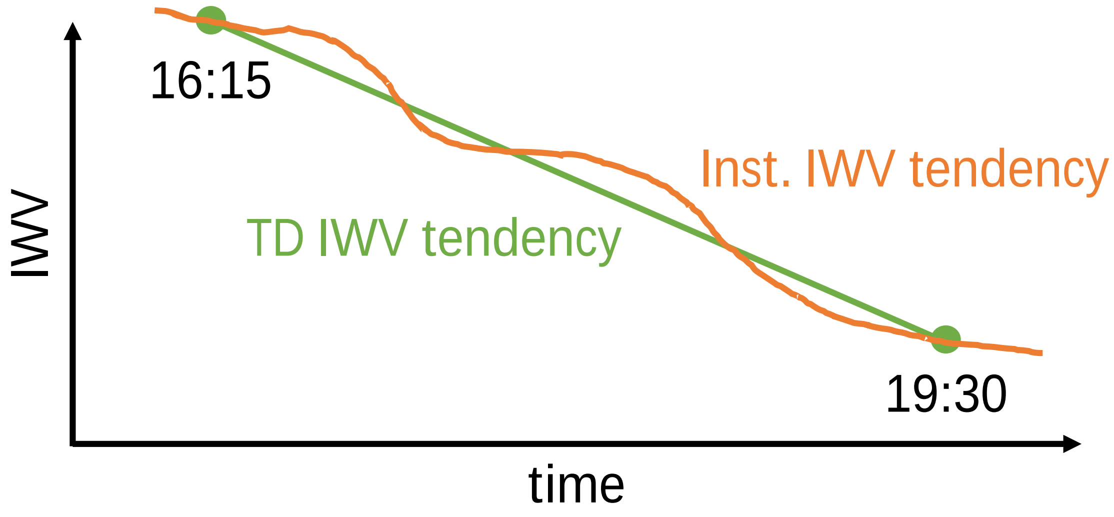
Budget closure if (within range of uncertainty)

Time Difference $\frac{\partial IWV}{\partial t}$ – Instantaneous $\frac{\partial IWV}{\partial t}$ = 0

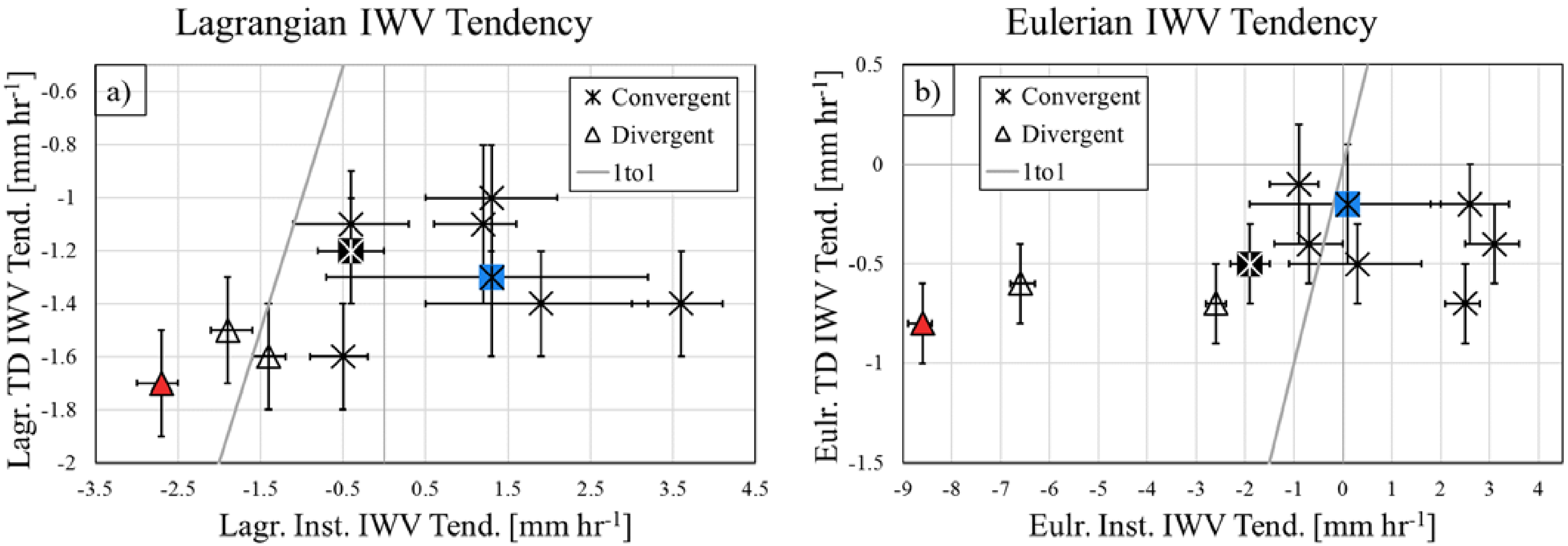
IWV Time Tendency

However…

We cannot really expect perfect closure because Instantaneous IWV Tendency and Time Difference IWV Tendency may have incommensurate time scales, especially for small subregions.



IWV Time Tendency



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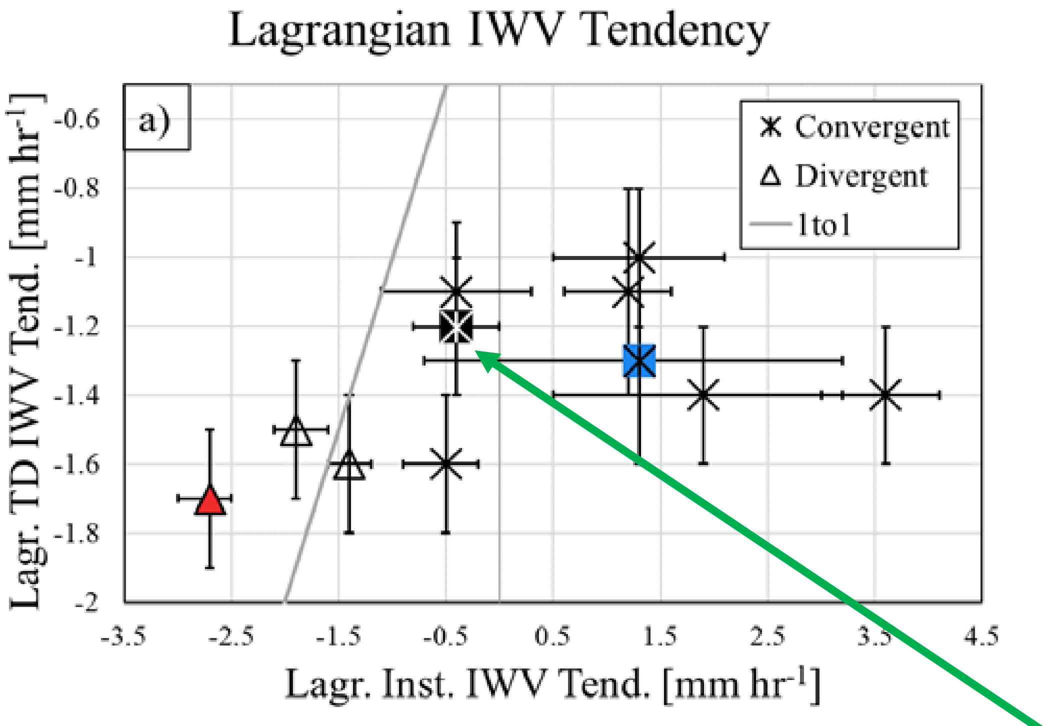
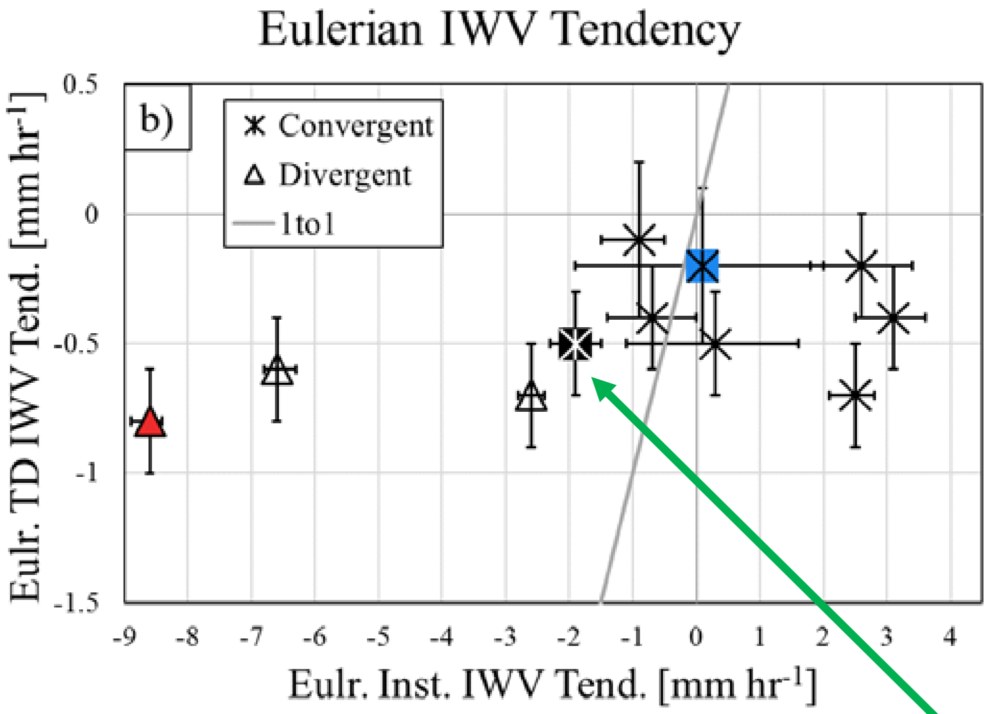
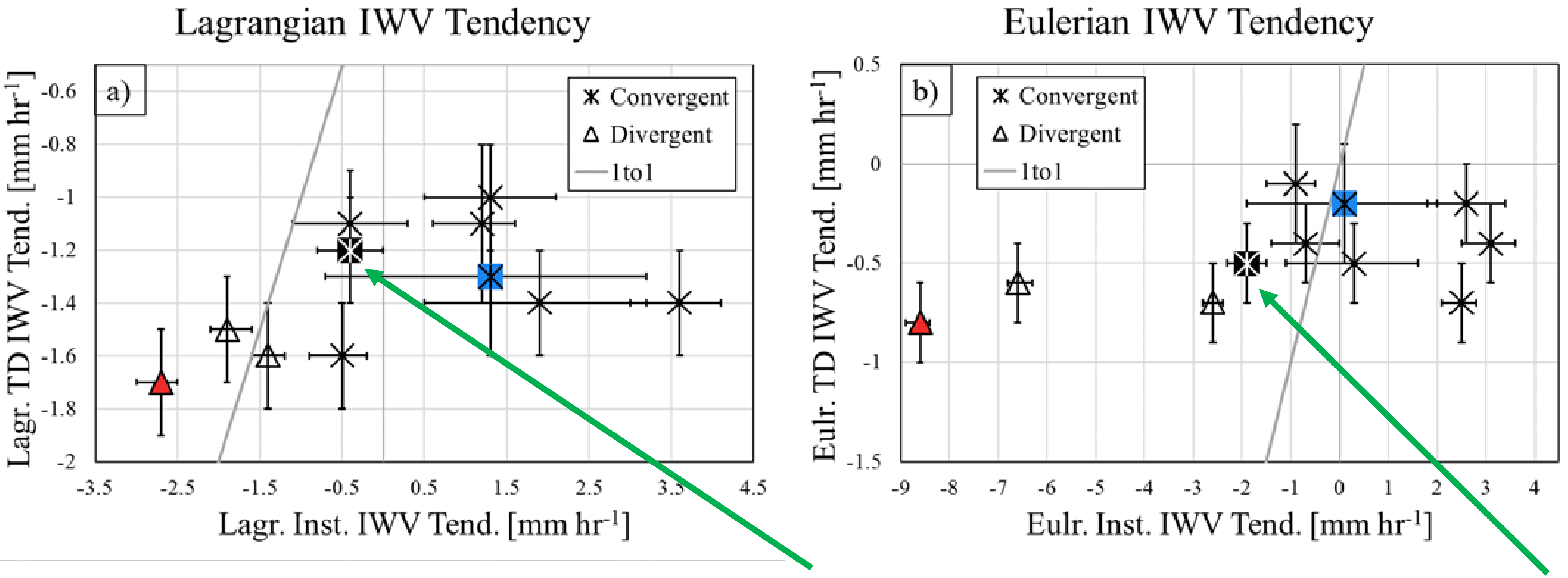




entire budget region

entire budget region

IWV Time Tendency



entire budget region

entire budget region

Closure might be better obtained for larger regions and shorter time scales.

Water Vapor Budget Terms for Entire Region

ADV = -1.54 ± 0.18 mm hr^{-1}

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Instantaneous Eulerian IWV Tendency = -1.85 ± 0.46 mm hr^{-1}

Time Difference Eulerian IWV Tendency = -0.52 ± 0.24 mm hr^{-1}

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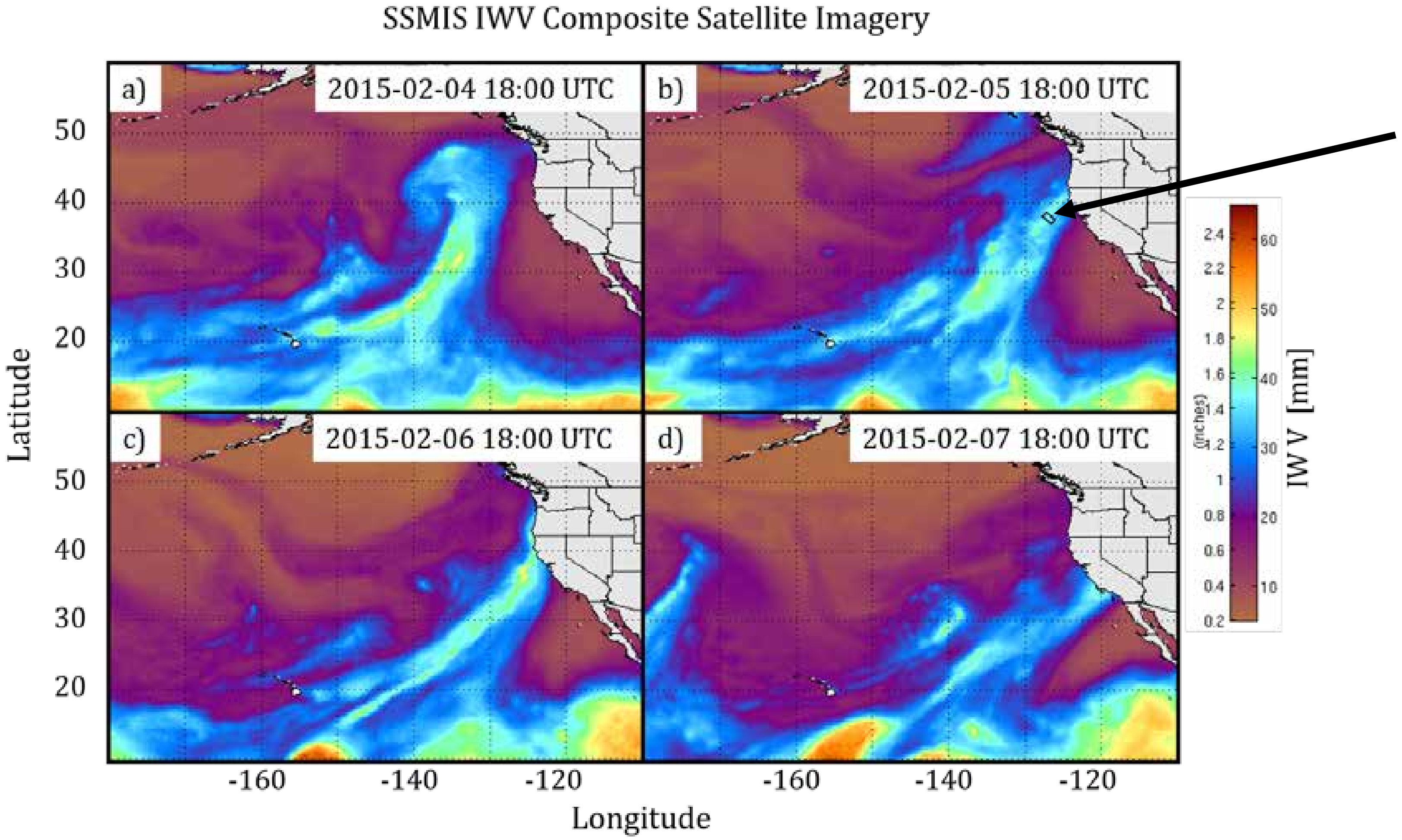
Key uncertainties

- Estimation of precipitation rate from airborne radar
- Independent measurement of IWV tendency by successive observations of the same region

Thank you!

Extra Slides

Satellite IWV for 4-7 February 2015

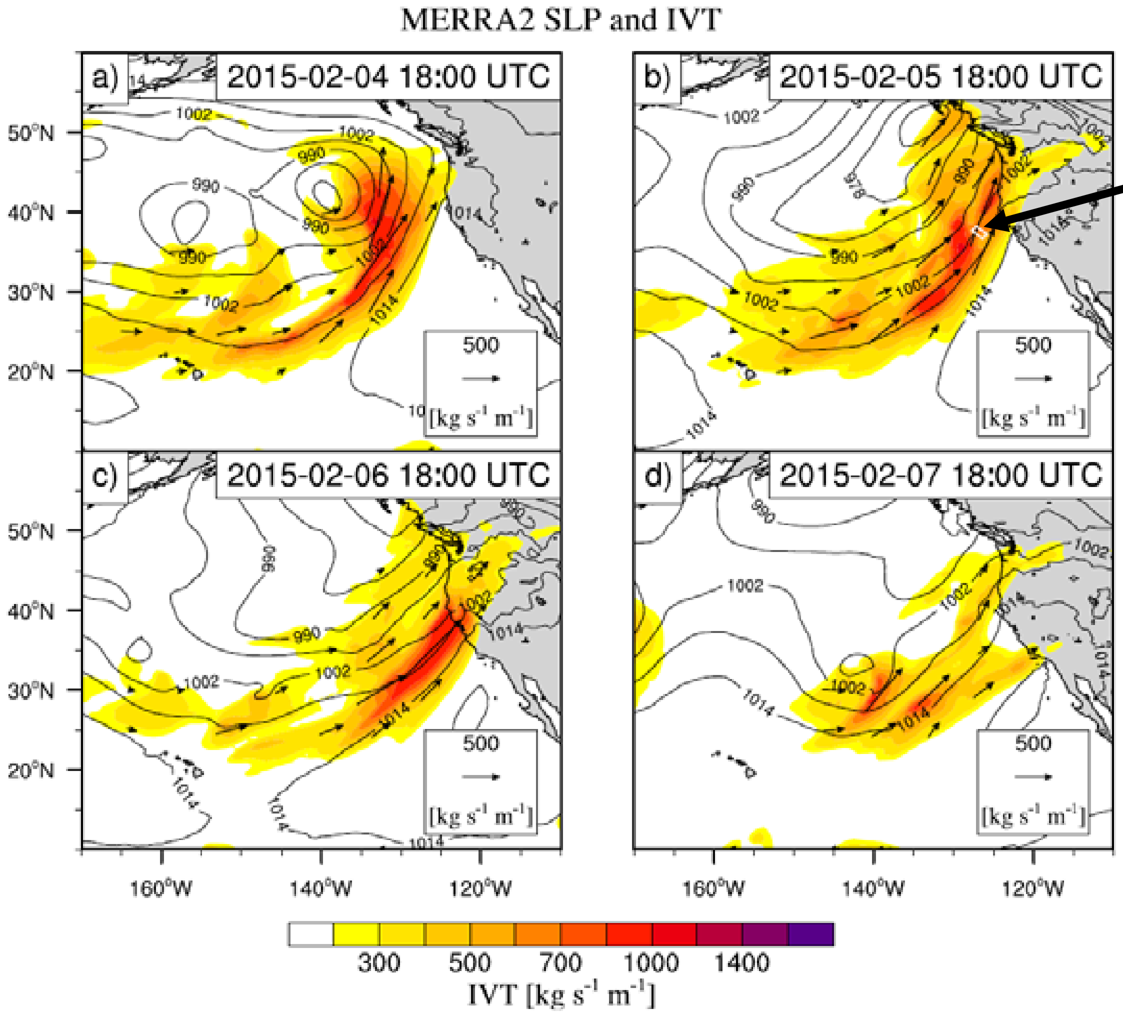


Water vapor budget region

IWV » 40 mm

Following landfall at
Northern California coast
48-hr precipitation > 250 mm

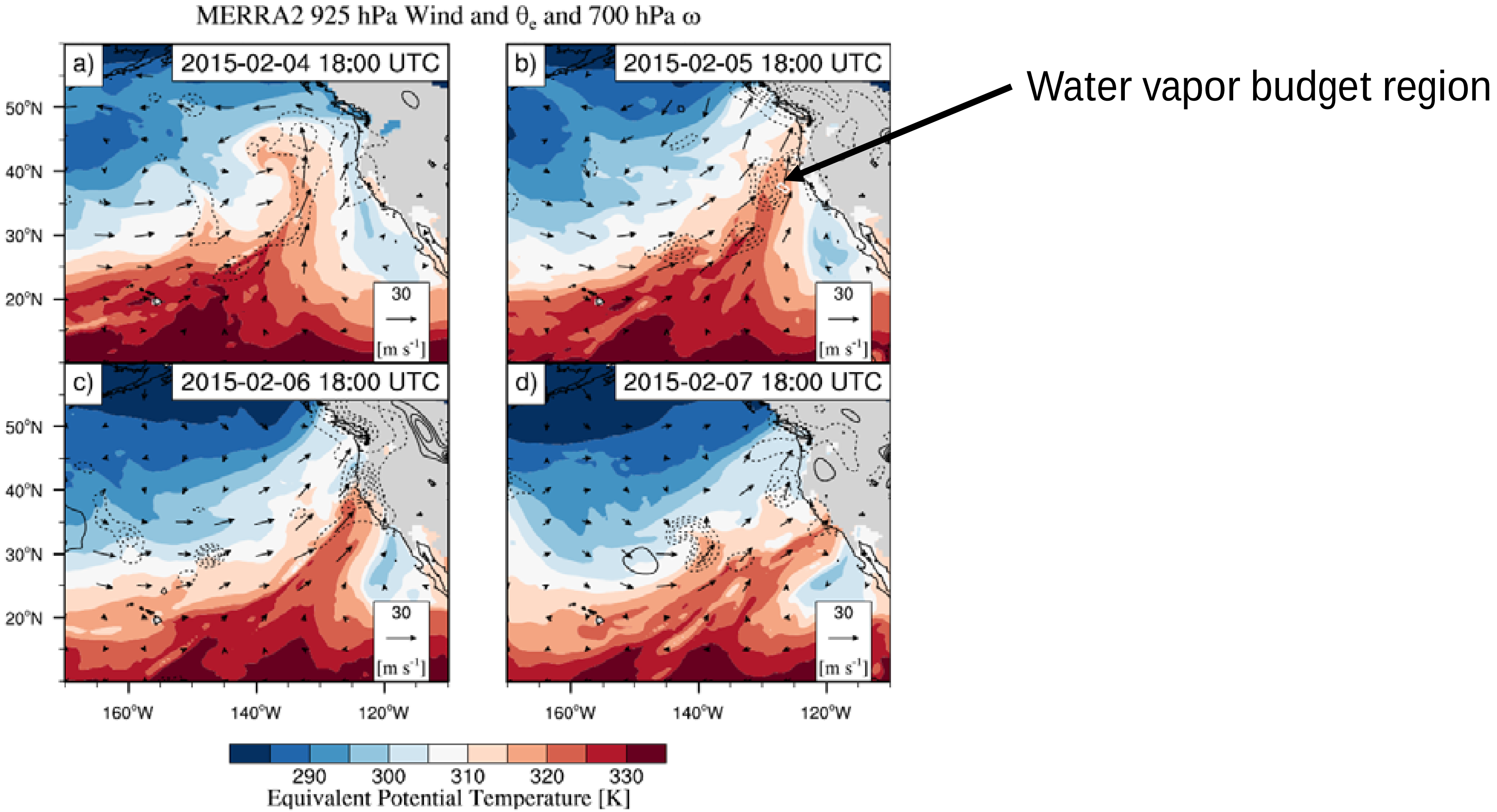
MERRA2 SLP and IVT for 4-7 February 2015



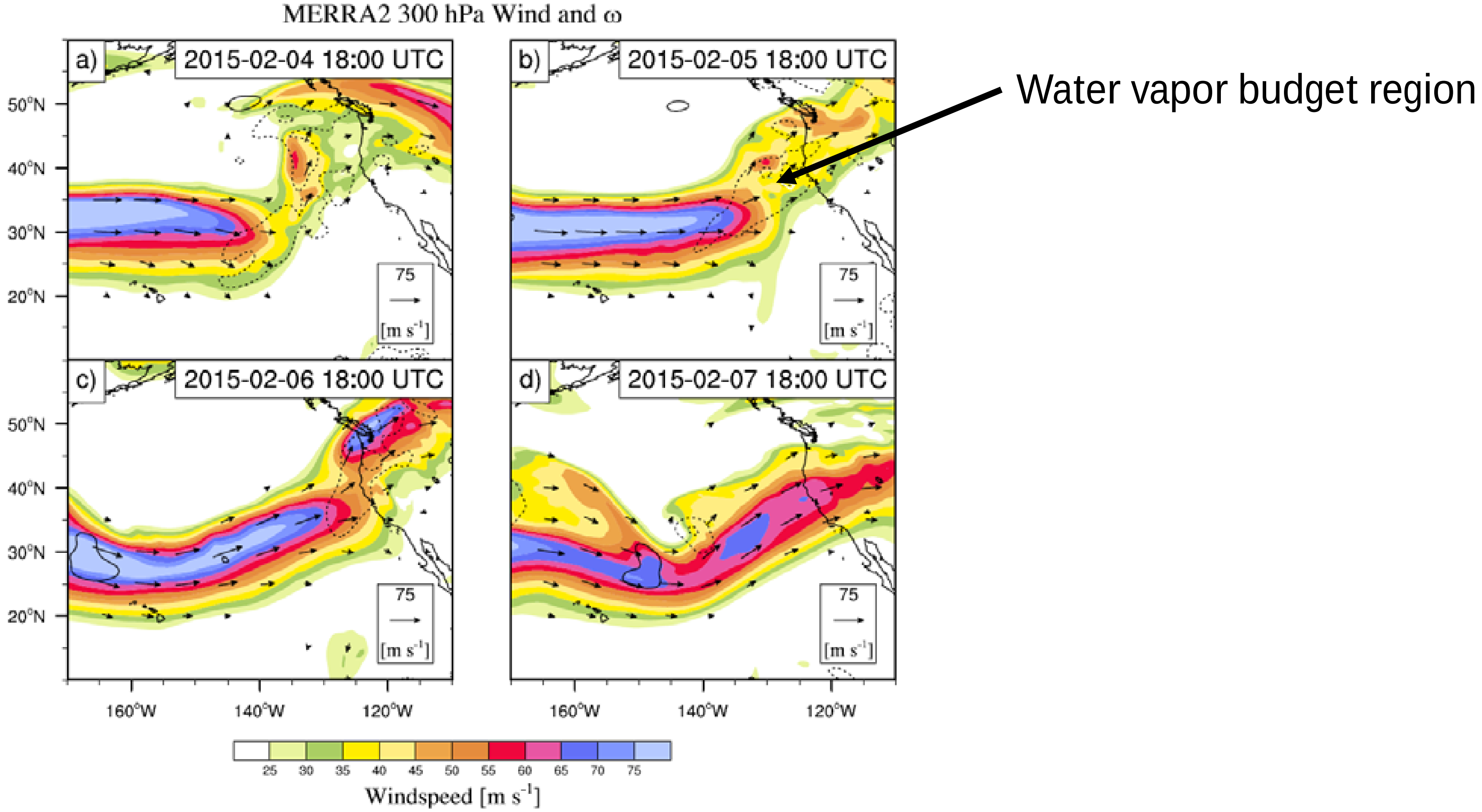
Water vapor budget region

IVT » 1070 kg s^{-1} m^{-1}

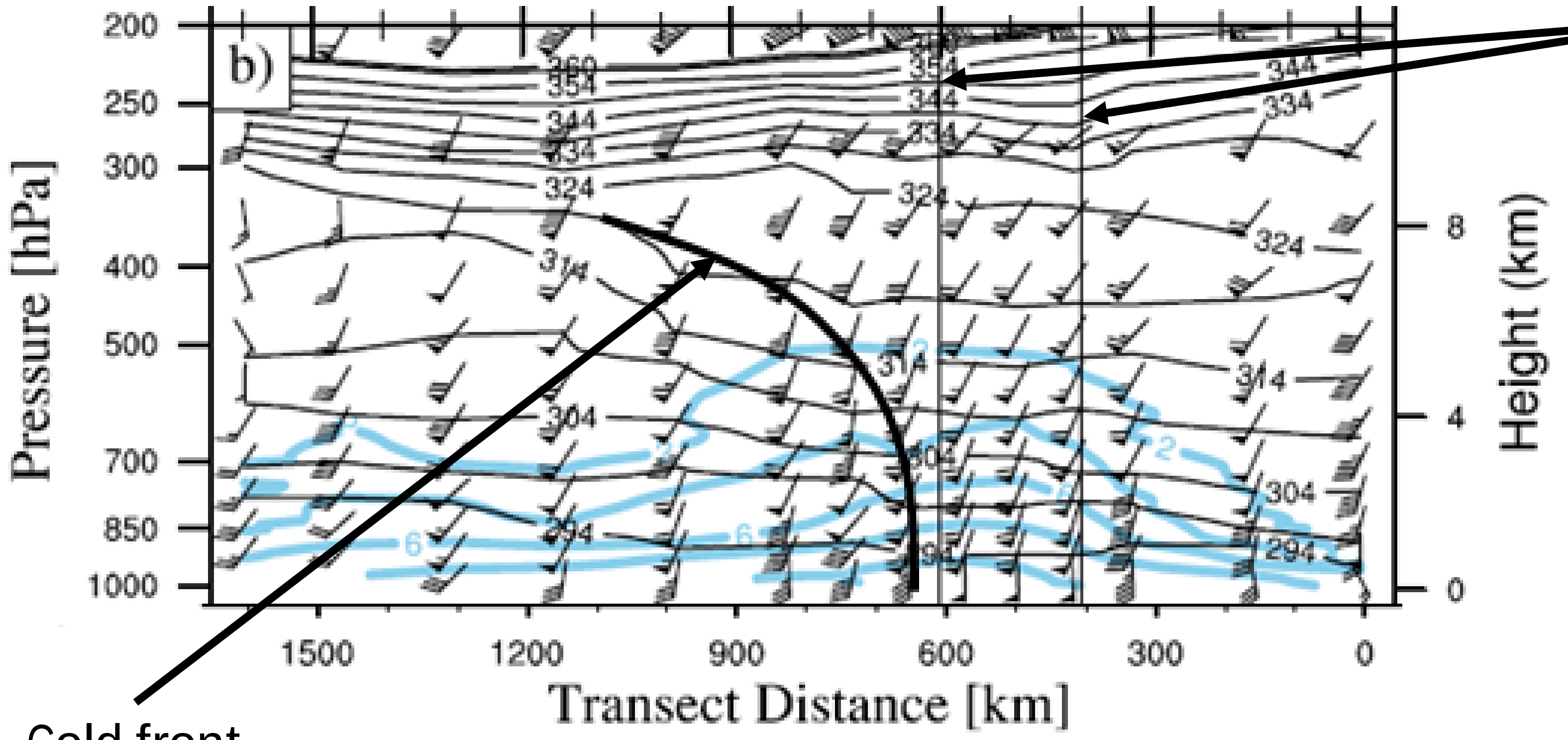
MERRA2 V_{925}, q_{925}, w_{700} for 4-7 February 2015



MERRA2 V_{300}, w_{300} for 4-7 February 2015



Dropsonde X-Section (*V*, q, q)



Cold front

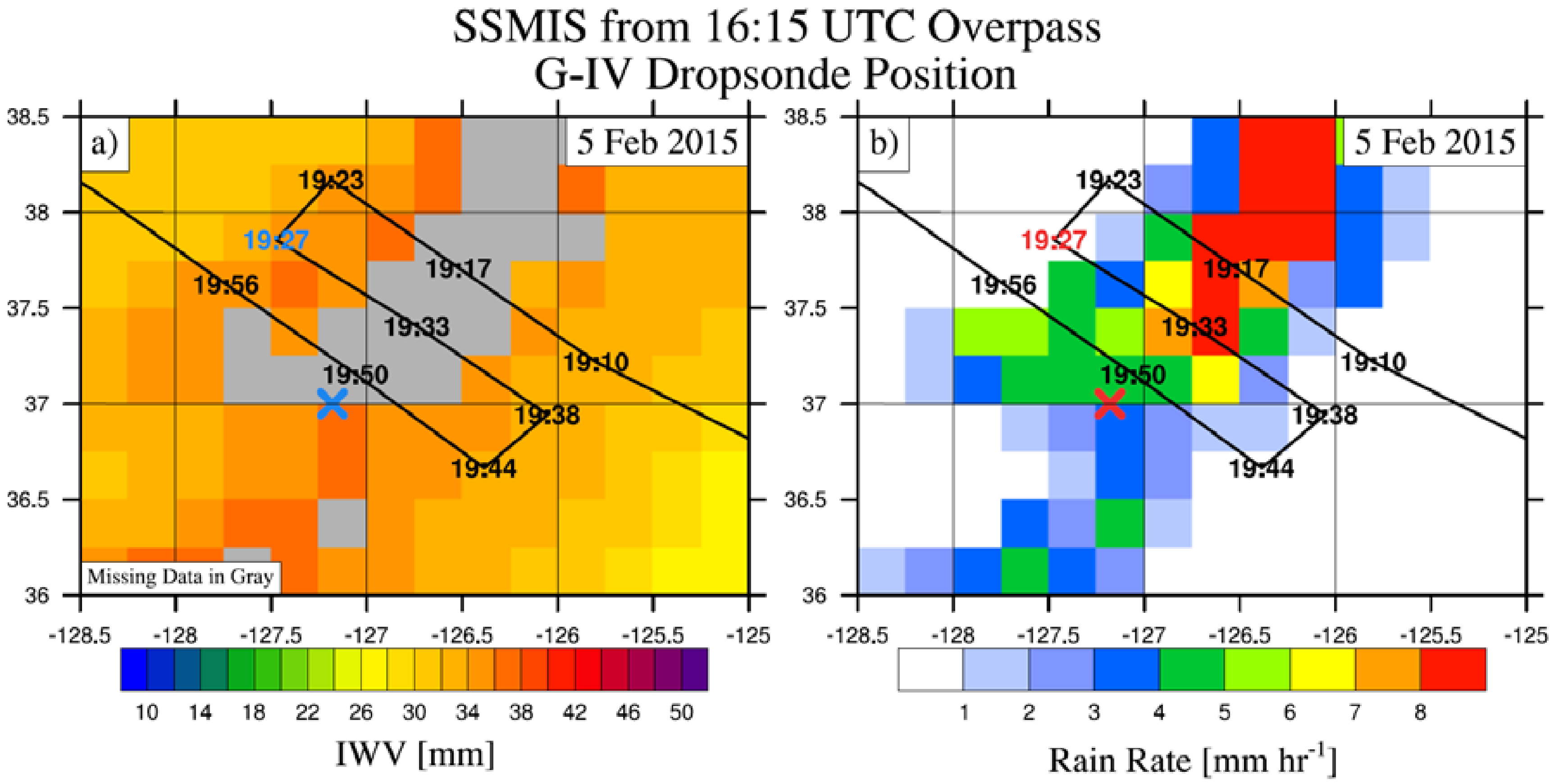
Water vapor budget region

Approximately barotropic

Small vertical wind shear

Max specific humidiy is 10.6 g kg^{-1}

Budget Region Dropsonde Times & Positions

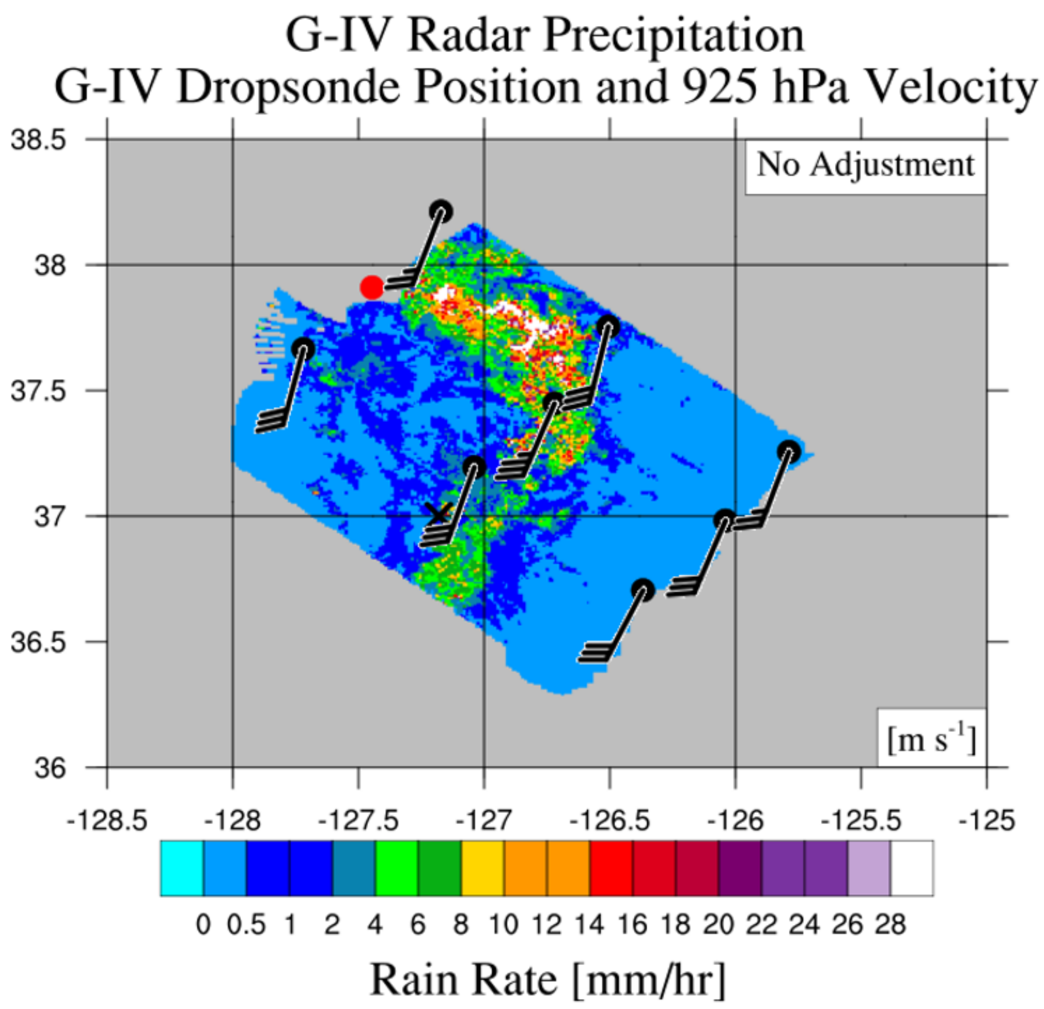


Release time is displayed

Background images are satellite IWV and rain rate from 16:15 UTC (3.25 hours earlier)

No time-to-space adjustment of dropsondes or satellite images

Budget Region Radar-Estimated Precipitation



Radar-estimated rain rate at 1-1.5 km MSL

Dropsonde positions are offset from radar swath center because dropsondes drift during the time it takes to descend to the elevation measured by radar

No time-to-space adjustment of radar swaths or dropsondes

Budget Region Dropsonde Profiles