Observing Atmospheric Rivers with NASA's Current and Next Generation Satellite Missions

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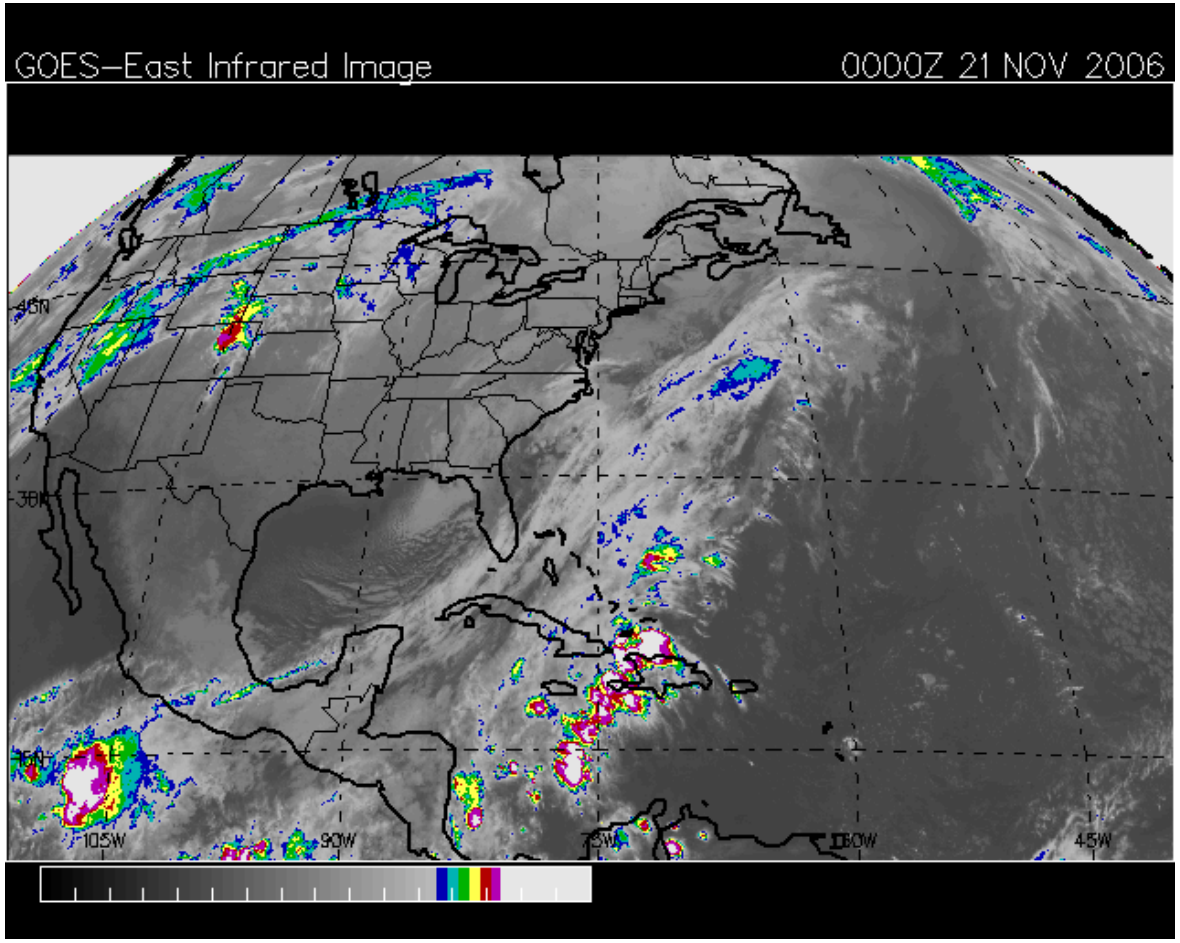
Multi-Dimensional Observations from Space

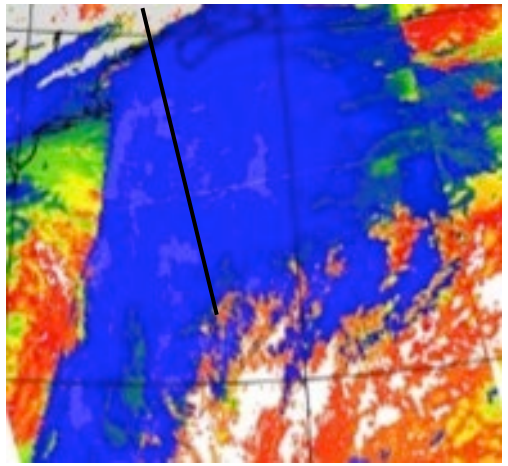
- Passive IR and visible measurements provide excellent spatial context
- It is only possible to view the top of the cloud
- Underlying vertical structure is hidden
- Passive and active (radar, GNSS) microwave measurements provide information on below-cloud horizontal and vertical structure

GOES IR Imagery 21-26 Nov 2006



Multi-Dimensional Observations from Space
1800 UTC 22 Nov 2006 (Crespo et al. 2016)

MODIS Cloud Top Pres



Multi-Dimensional Observations from Space 0600 UTC 24 Nov 2006 (Crespo et al. 2016)

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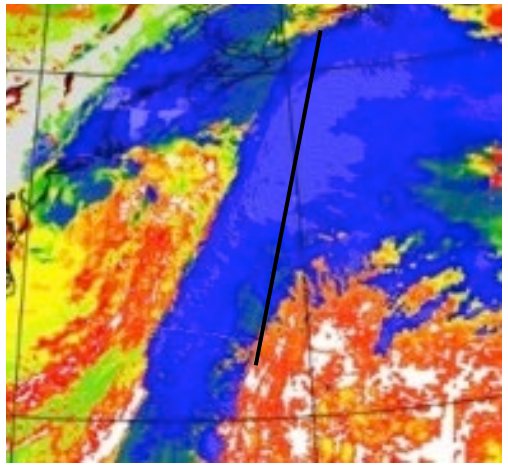

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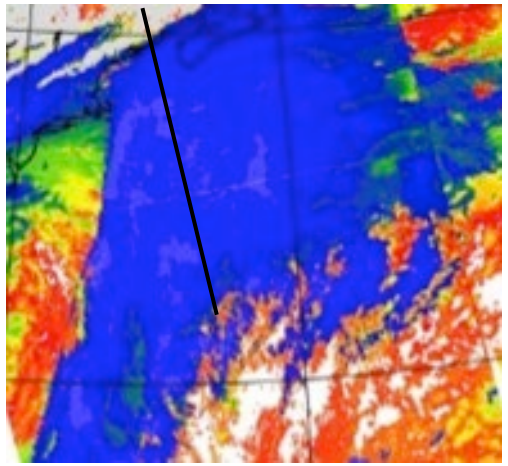
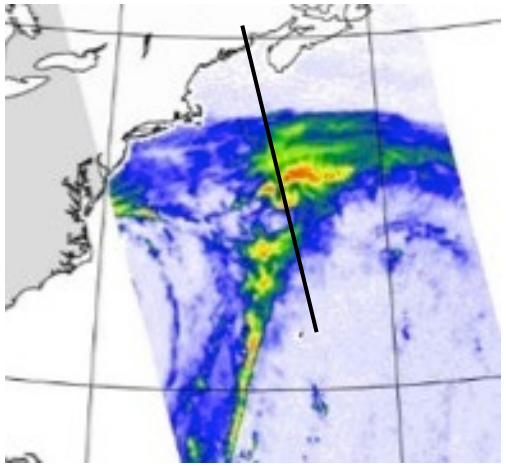
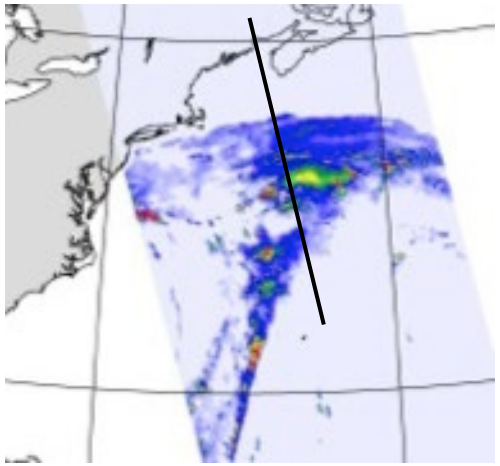


AMSR-E Cloud Water



AMSR-E Precip Rate



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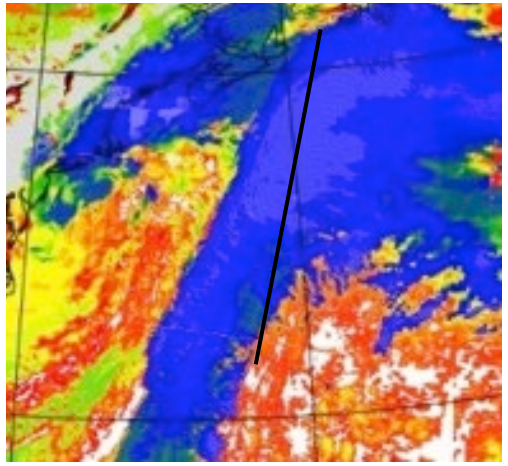

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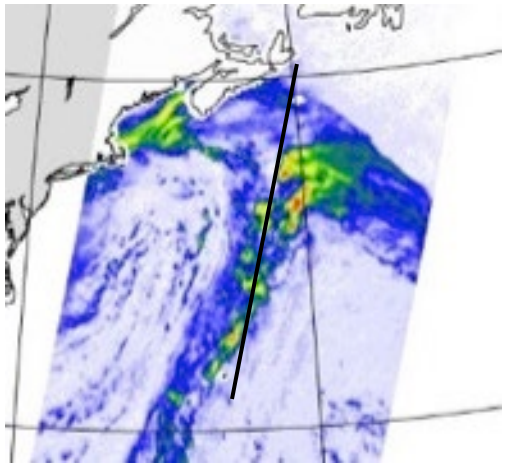

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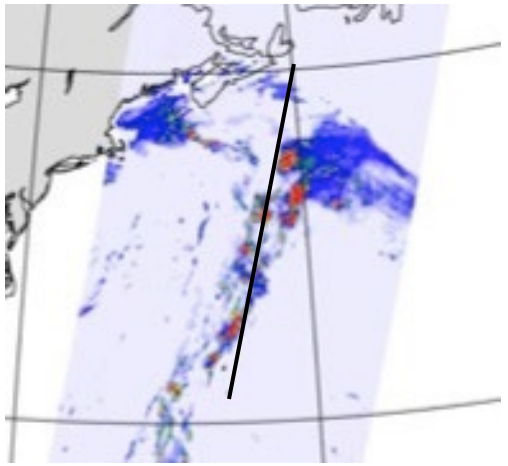

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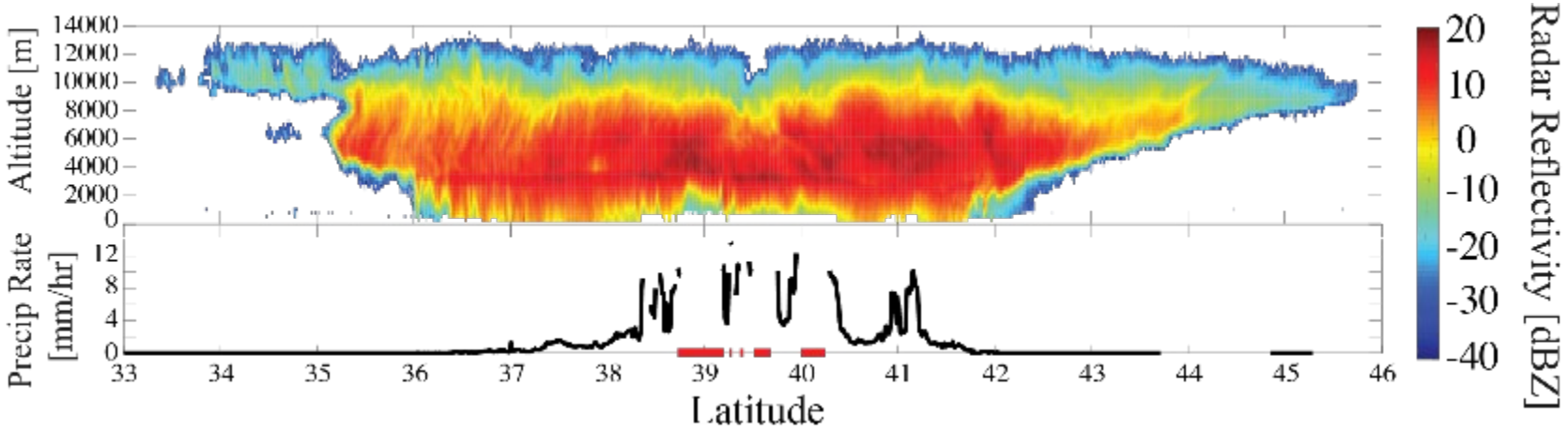

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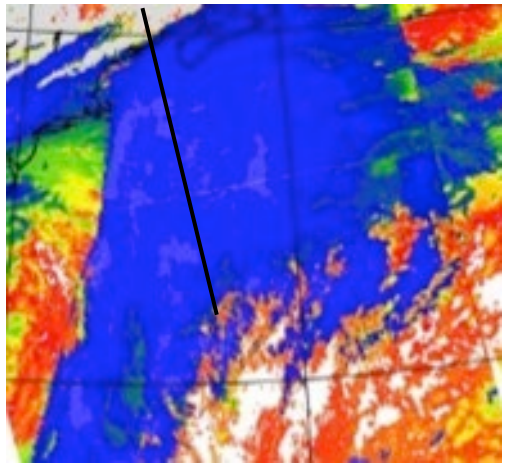

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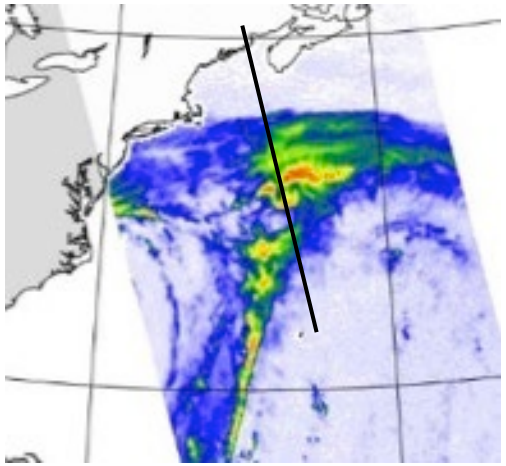

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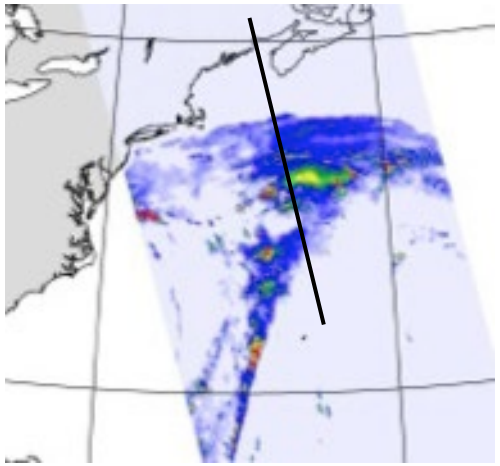

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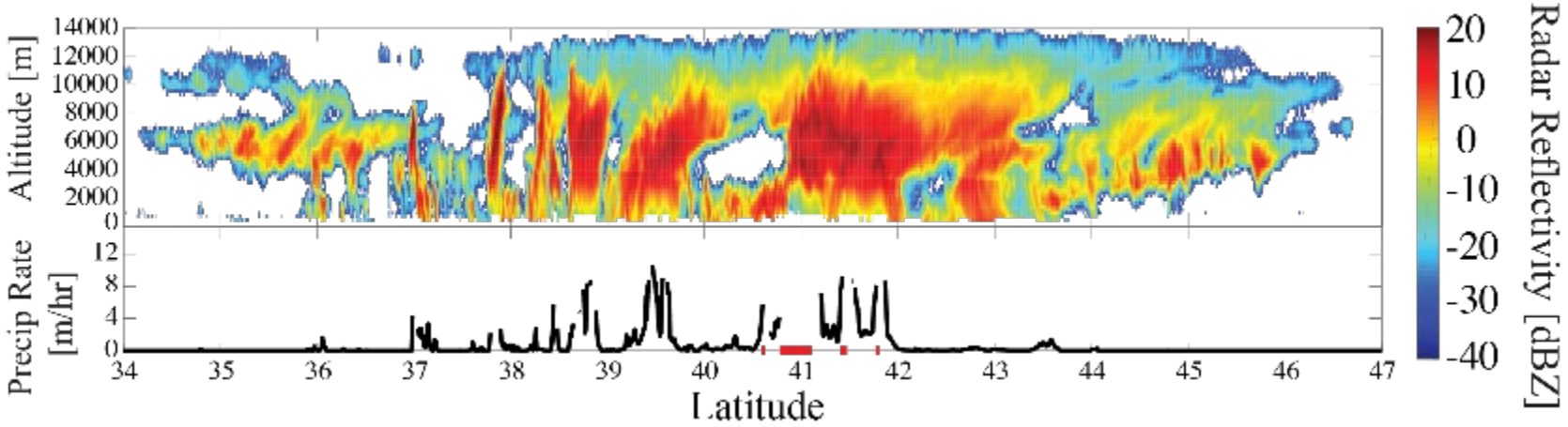

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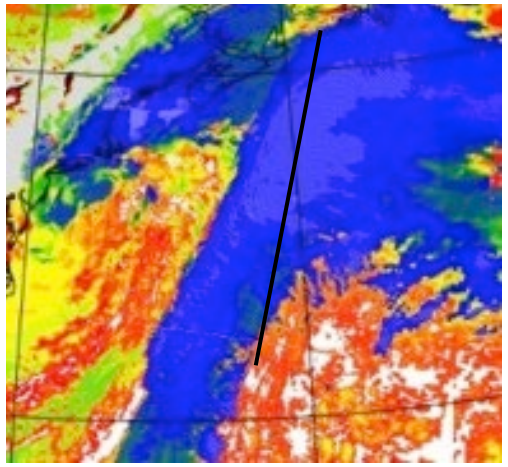

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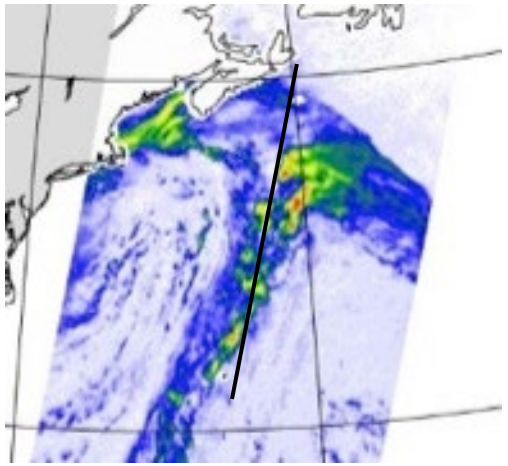

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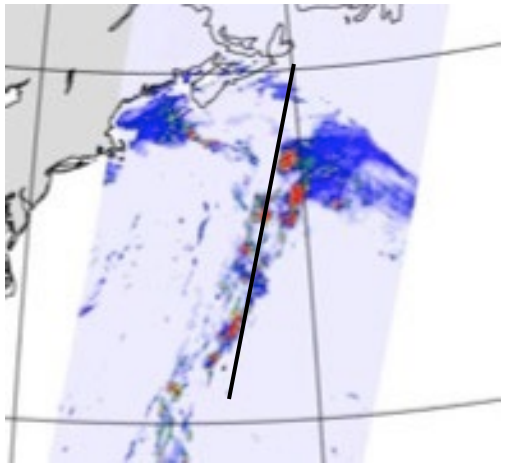
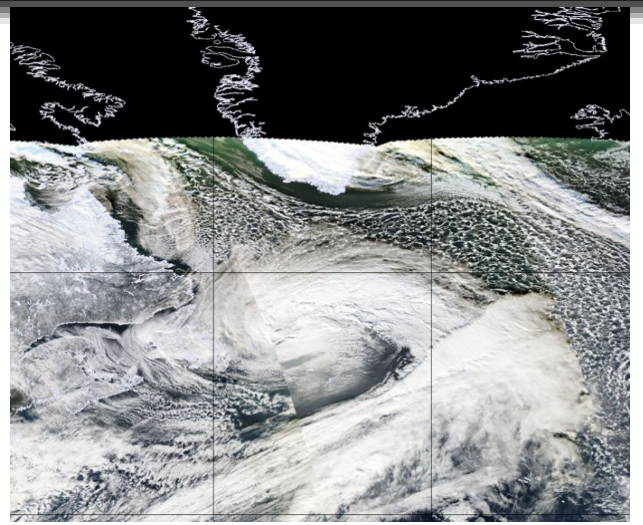
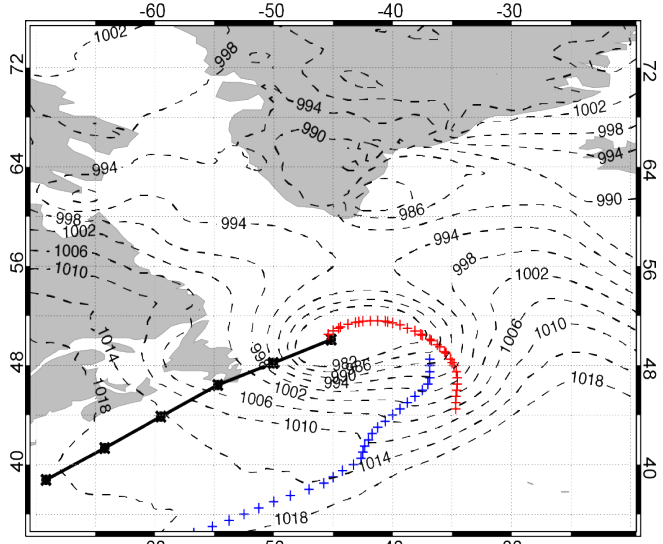


Composite Analysis of Observed ETCs and ARs

- Cyclone centers, fronts, and AR's objectively identified using gridded analysis data (Bauer et al. 2016; Guan and Waliser, 2017)
- Find where low Earth orbiting satellites (e.g., MODIS, CloudSat/CALIPSO, AMSR, CYGNSS, and GPM) intersect fronts and composite them
- Examine the properties of clouds and their relationship to the thermodynamic environment and AR and cyclone strength

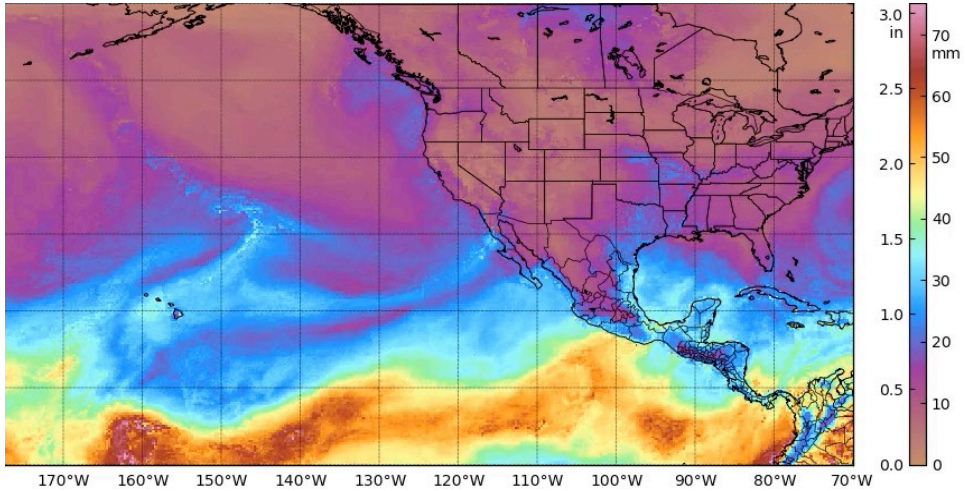




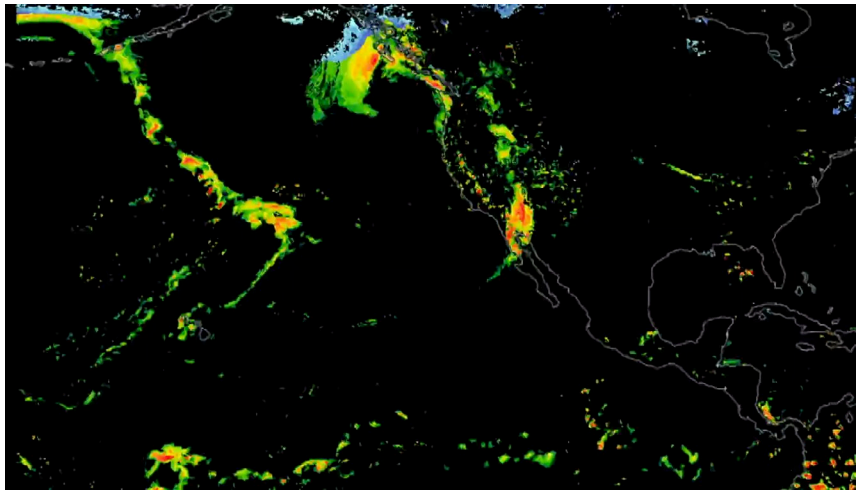
Research Spans Multiple Decades

- Naud et al: Satellite + Reanalysis Composite Analysis
  - 2006: ETC cloud phase
  - 2012, 2013, 2015: Warm and cold front vertical structure
  - 2016, 2017: Aerosol distribution around ETCs
  - 2021, 2023: Ocean surface heat fluxes in and around ETCs
- A host of studies evaluating ETCs in models and reanalysis
- We have a long enough data record to explore the influence of moist processes on AR's from observations

Microwave-Based PW



Satellite-Based Precipitation Rate



Influence of Convection on AR's

Consider the following hypotheses:

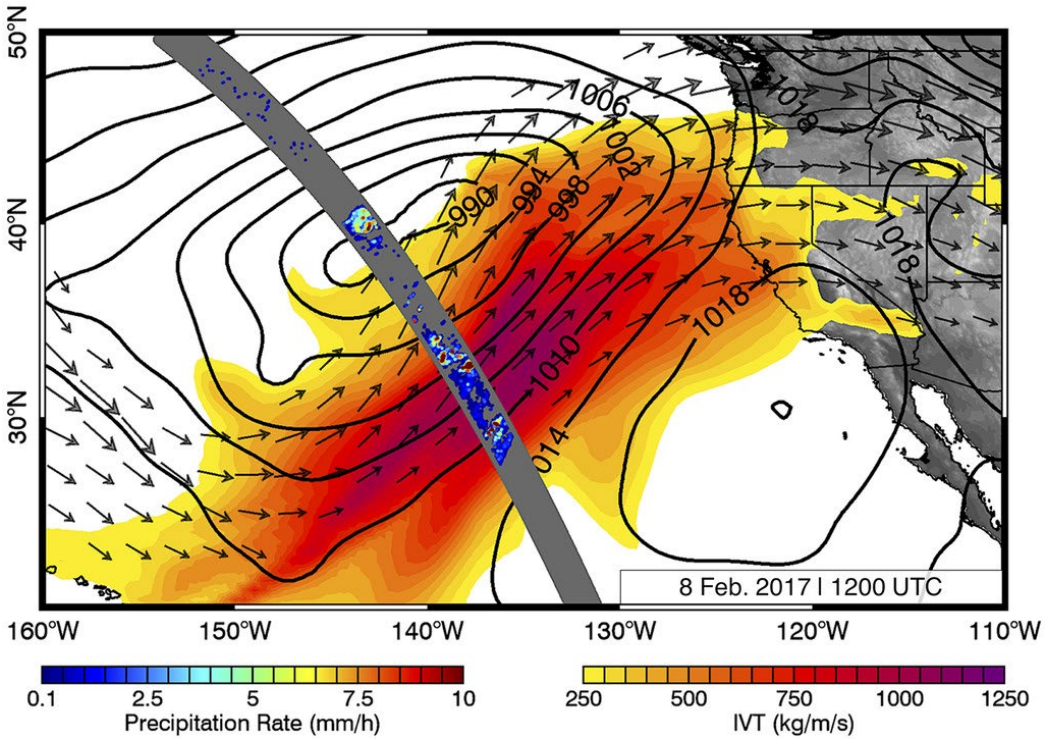
1. **H1**: Convection early during development deprives ARs of moisture, thereby reducing their precipitation production later in life.

2. **H2**: Convection early during development enhances AR precipitation production through the impact of associated latent heat release on synoptic dynamics.

3. **H0**: Convection early during development has no impact on AR precipitation production

Atmospheric River Composites Radar and Microwave Data from GPM

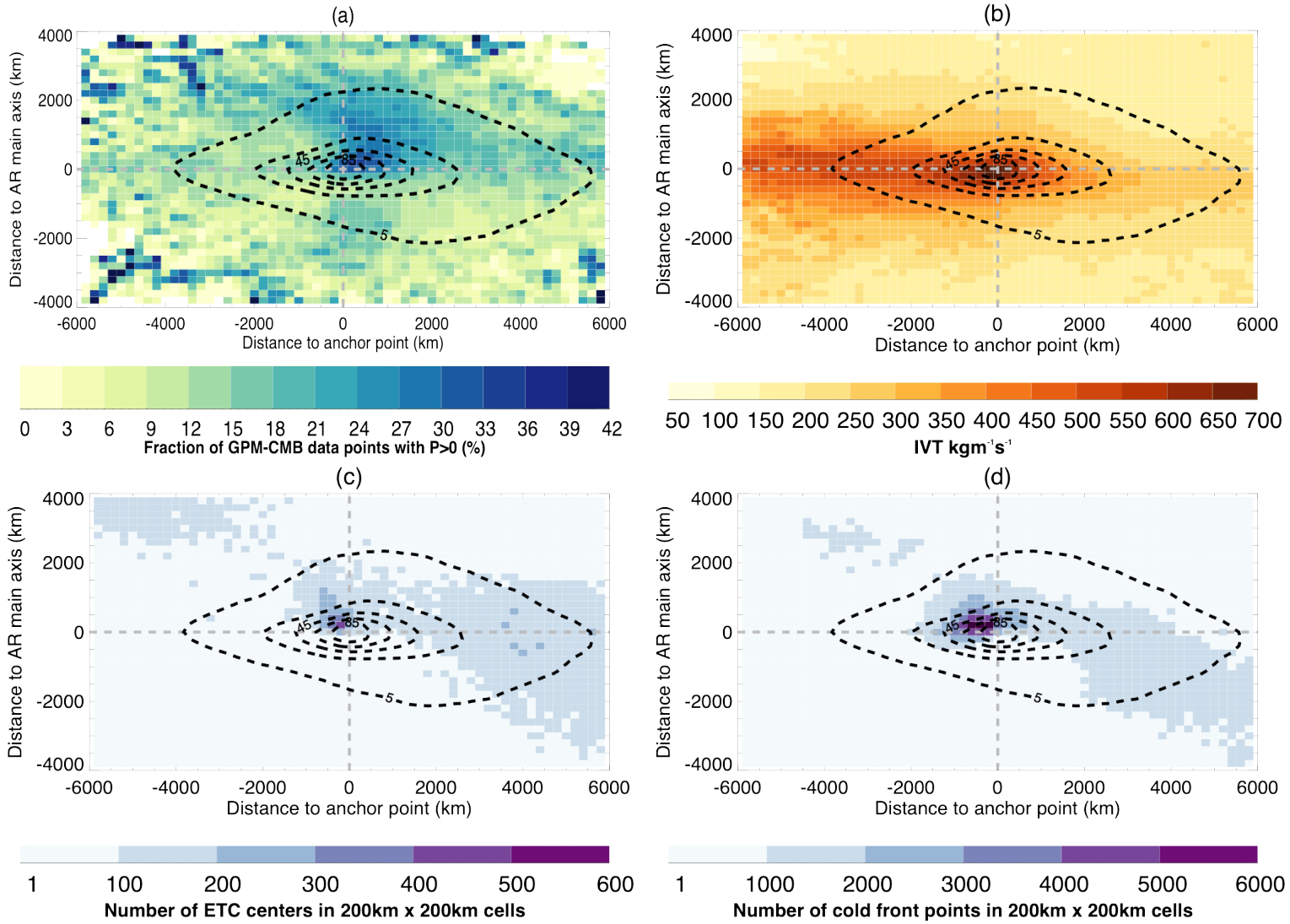
- Use Guan and Waliser criterion applied to MERRA-2, and collocate ARs with GPM overpasses
- 43,451 ARs with a GPM overpass during 2015-2024
- For each set (GPM & MERRA2):
  - Extract data in AR footprint.
  - Apply rotation and regridding for each AR
  - Composite data (mean, median) for all or subsets of AR using the same anchor and main direction axis



Cannon et al., 2020, Mon. Wea. Rev.

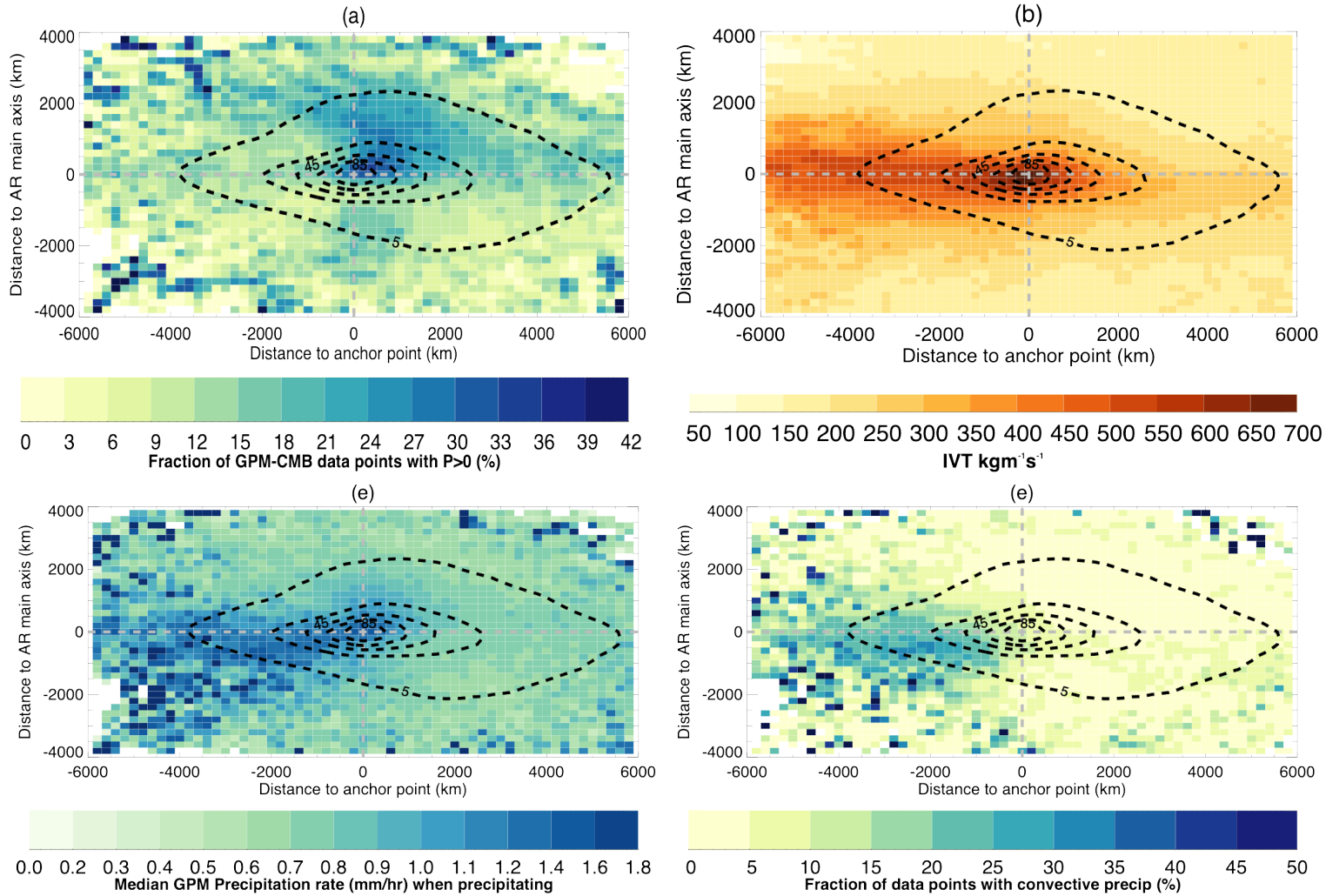
Precipitation Occurrence and Rate
Naud et al. (2026; Cli. Dyn.)

- Composites centered on max IVT, rotated to common coordinate system
- AR's most often occur in proximity to a low pressure center and cold front



Precipitation Occurrence and Rate
Naud et al. (2026; Cli. Dyn.)

- Precipitation occurrence maximized along and downstream of IVT max
- Precipitation intensity maximized upstream of IVT max
- Most intense precipitation associated with convection

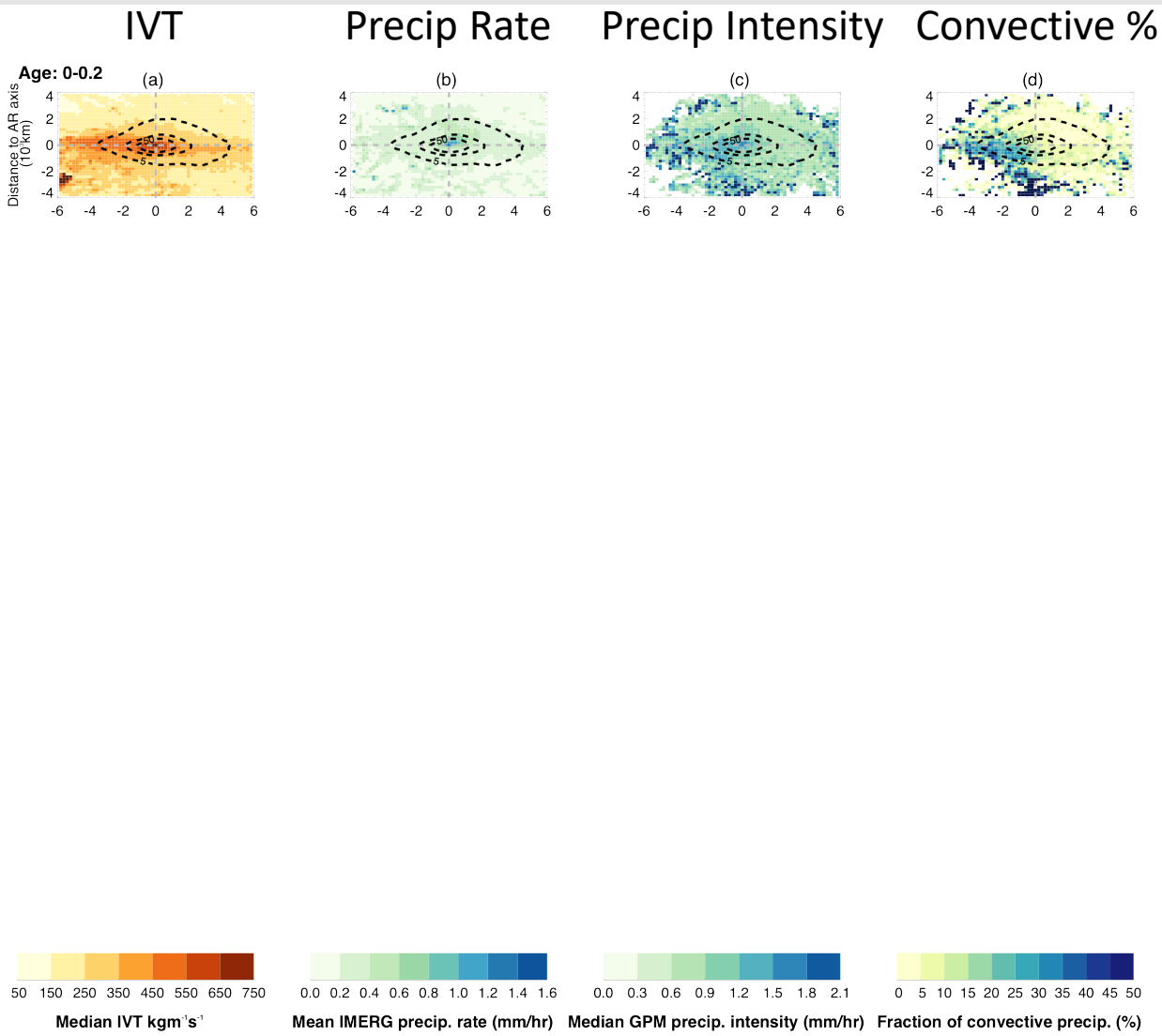


IVT and Precip vs AR Life Stage - Means

Naud et al. (2026; Cli. Dyn.)

- Normalize each AR life cycle into 5 stages from initial to final detection
- Largest IVT occurs in stages 1 and 2
- Mean precipitation follows IVT
- Precipitation intensity and convective fraction peak early and decline later

Stage 0



IVT and Precip vs AR Life Stage - Anomalies

Naud et al. (2026; Cli. Dyn.)

- Normalize each AR life cycle into 5 stages from initial to final detection
- Largest IVT occurs in stages 1 and 2
- Mean precipitation follows IVT
- Precipitation intensity and convective fraction peak early and decline later

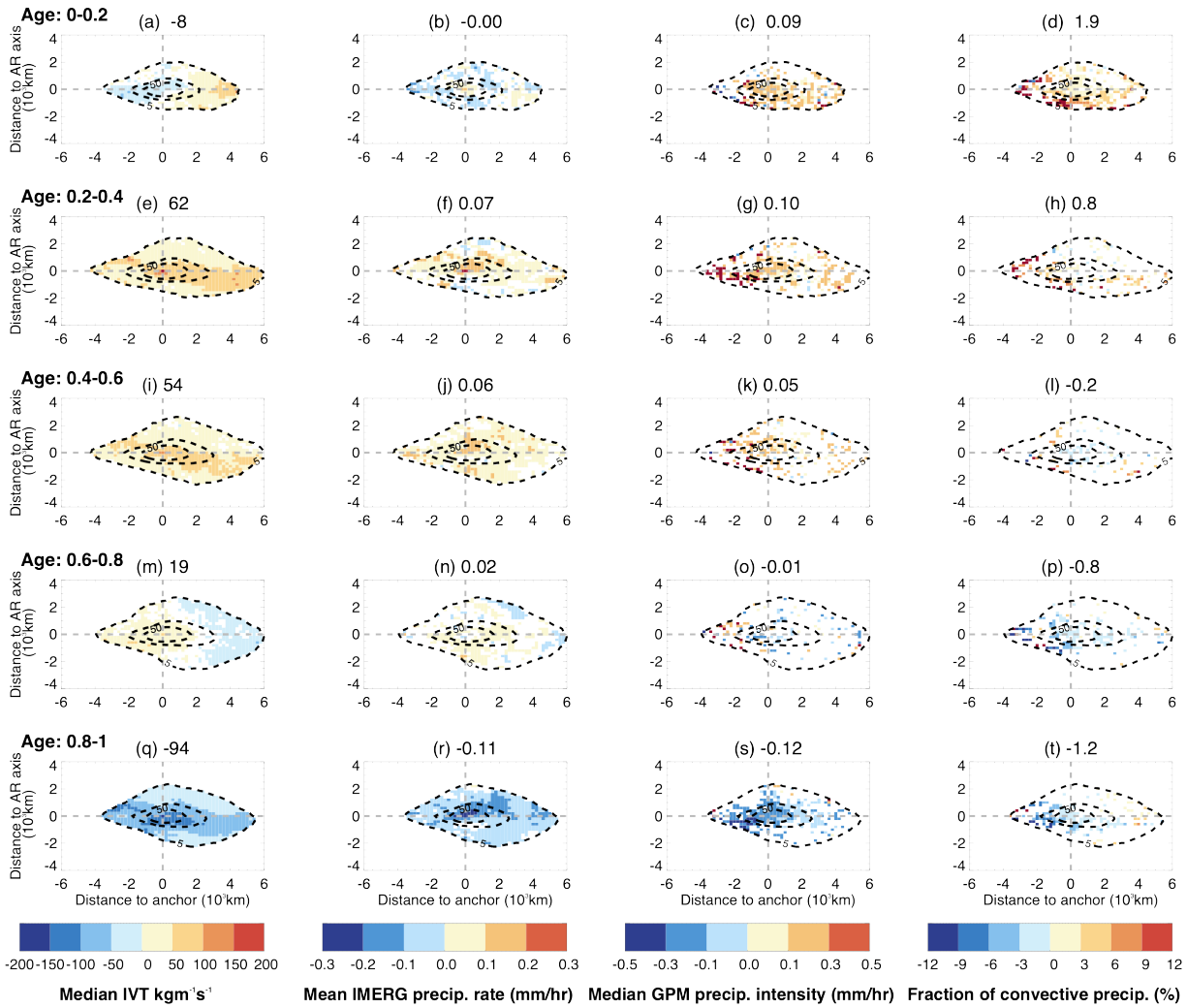
Stage 0

Stage 1

Stage 2

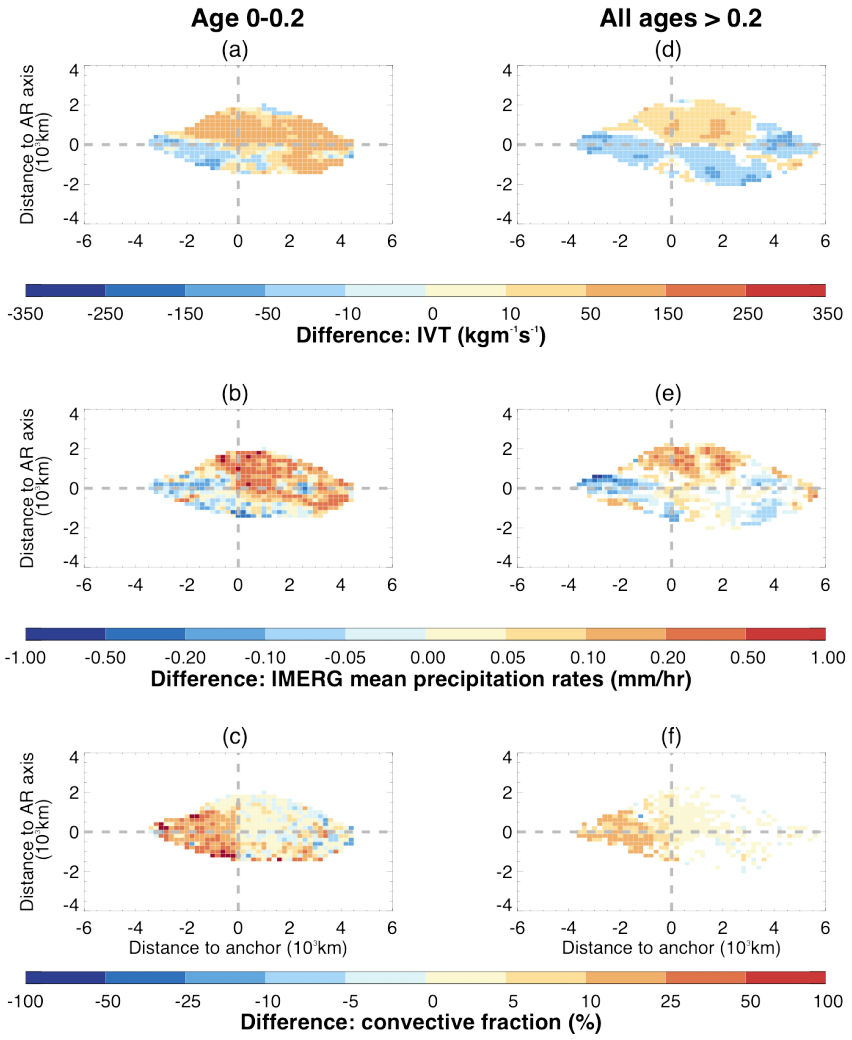
Stage 3

Stage 4



Convective Precip vs AR Life Stage – Early vs Late
Naud et al. (2026; Cli. Dyn.)

- Separate dataset into 1/3's by **convective fraction**
- Subtract composite fields for lowest 33% convective fraction from those with highest 33% convective fraction
- Patterns of IVT and mean precipitation match
- Convective fraction is clearly higher early in the life cycle
- The pattern of convective fraction differs from mean precipitation and IVT



Key Observation-Based Results

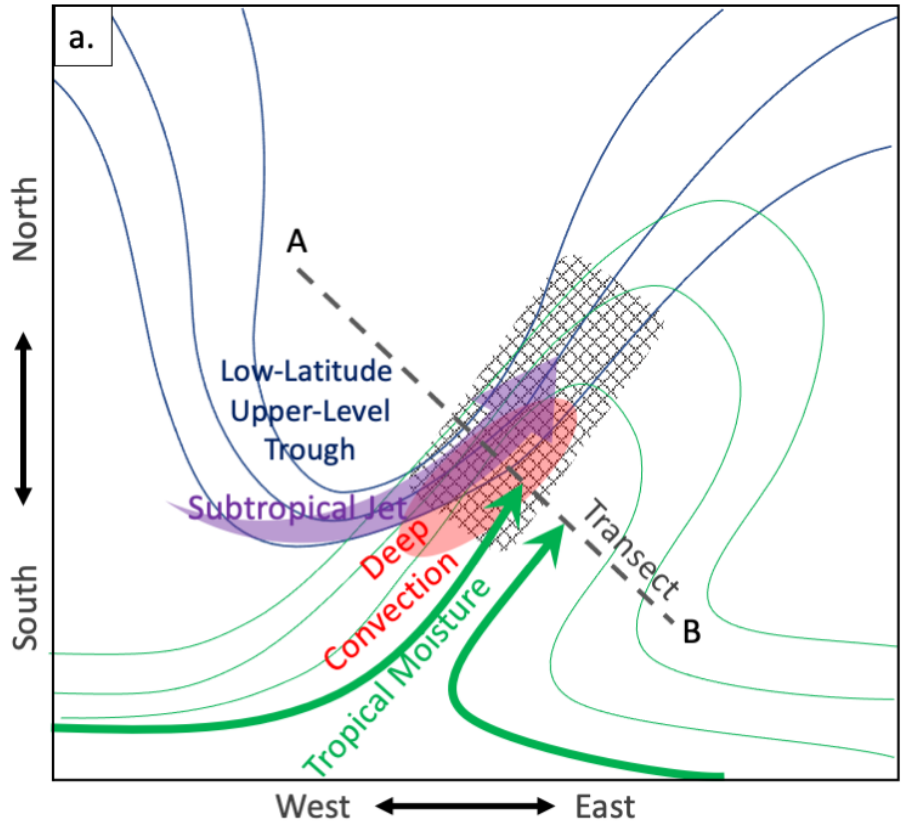
- Results suggest that there is a relationship between early-stage convection and precipitation production in ARs
- Convection fraction is maximized early in the life cycle, while IVT peaks later
- If synoptic conditions are favorable for convection, latent heating, PV production, and impact on cold front intensity may help intensify IVT.

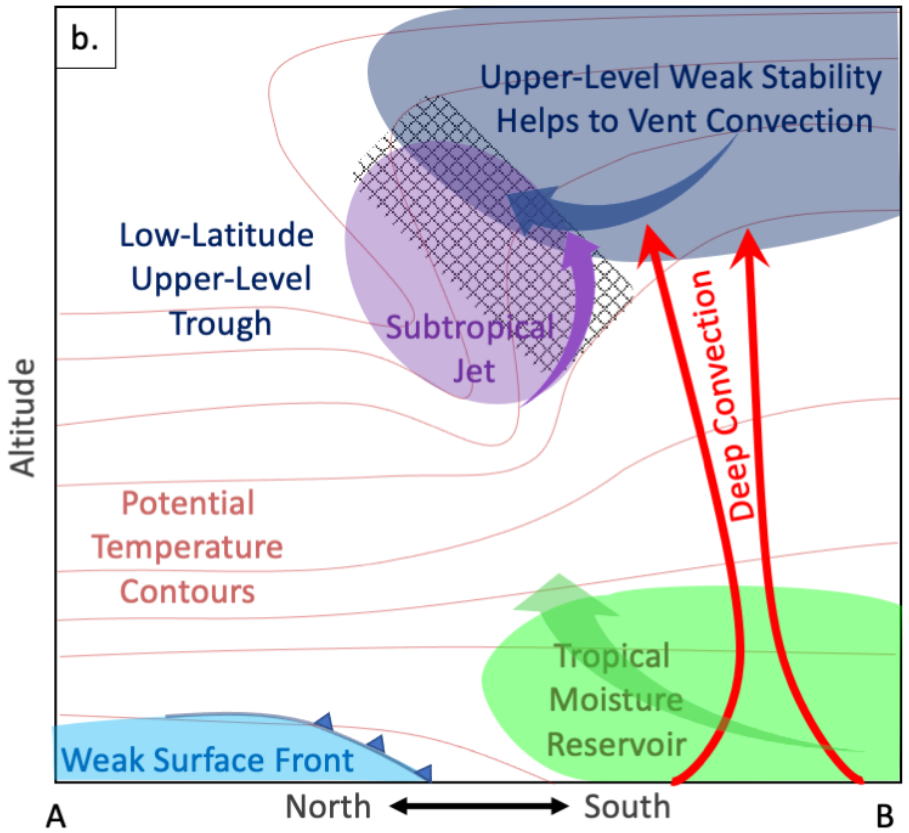
1. ~~**H1**: Convection early during development deprives ARs of moisture, reducing their precipitation production later in life.~~
2. **H2**: Convection early in AR development enhances AR precipitation production through the impact of associated latent heat release on synoptic dynamics.
3. ~~**H0**: Convection during early AR development has no impact on AR precipitation production~~

?

Driving Processes: Latent Heating
Cannon et al. 2017

- Influence of LHR on ETC storm dynamics has been known for decades: intensification of storms, changes in front and upper tropospheric structure

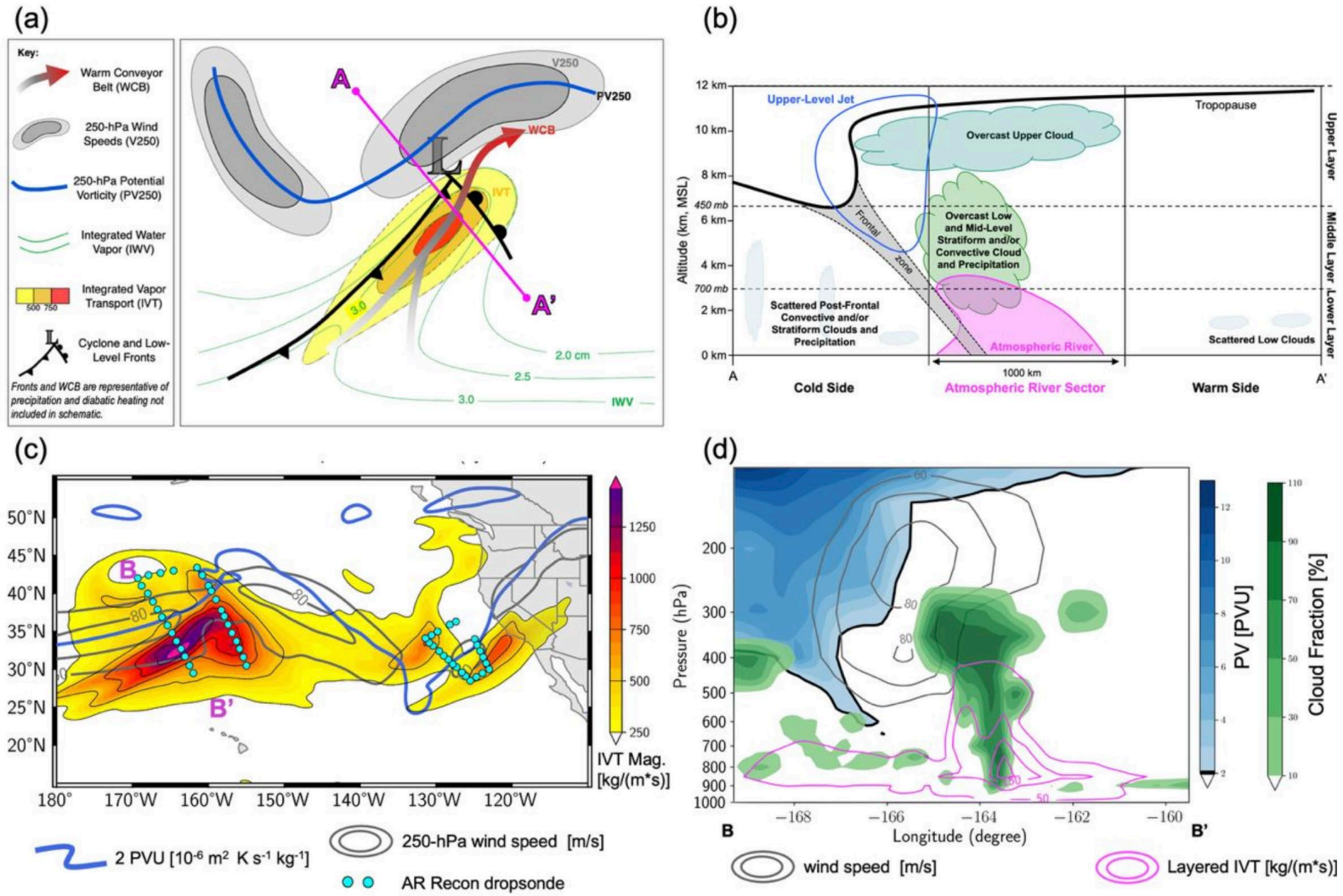




Figures adapted from Cannon et al., 2017 (J. Geophys. Res.)

Driving Processes: Latent Heating
Zheng et al. 2025

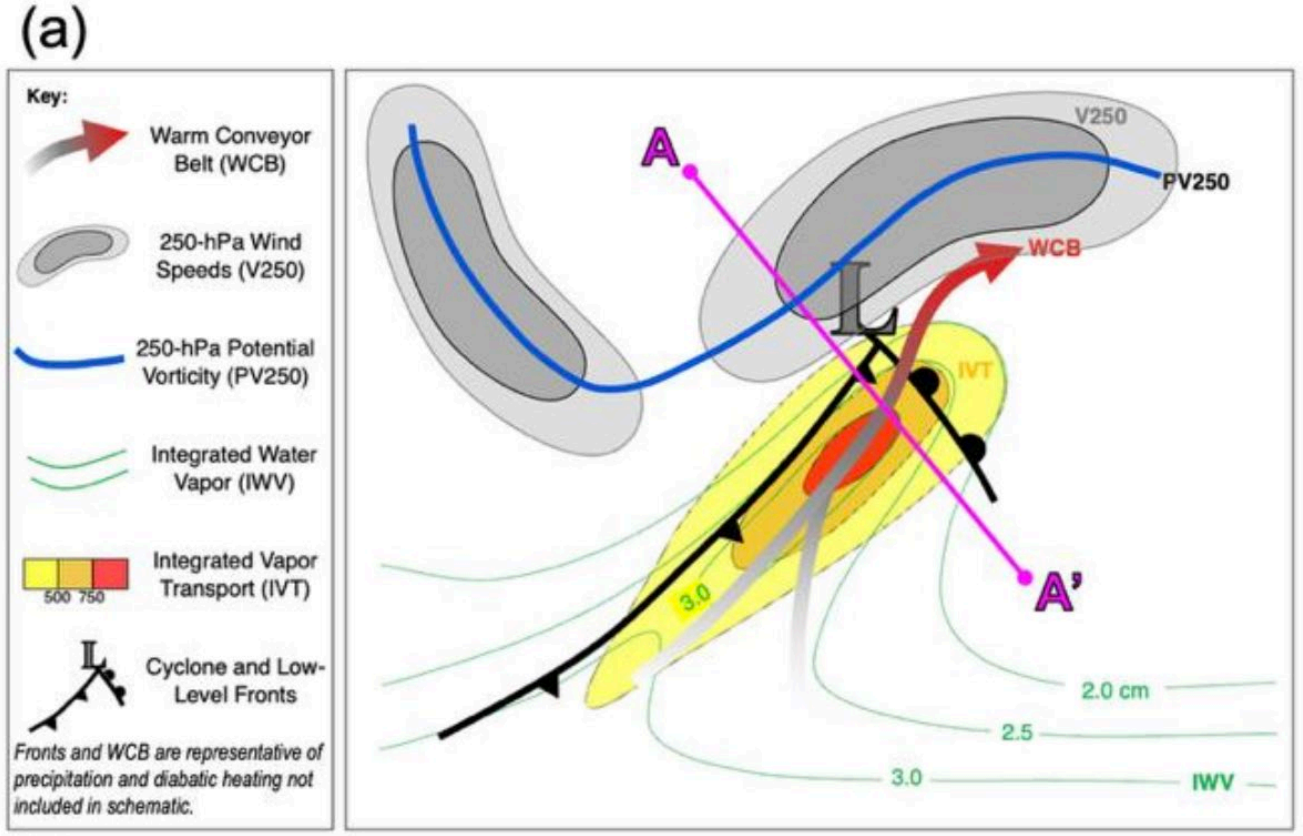
- Influence of LHR on ETC storm dynamics has been known for decades: intensification of storms, changes in front and upper tropospheric structure
- Zheng et al., (2025, BAMS)
- Need models as a laboratory to explore influence of processes

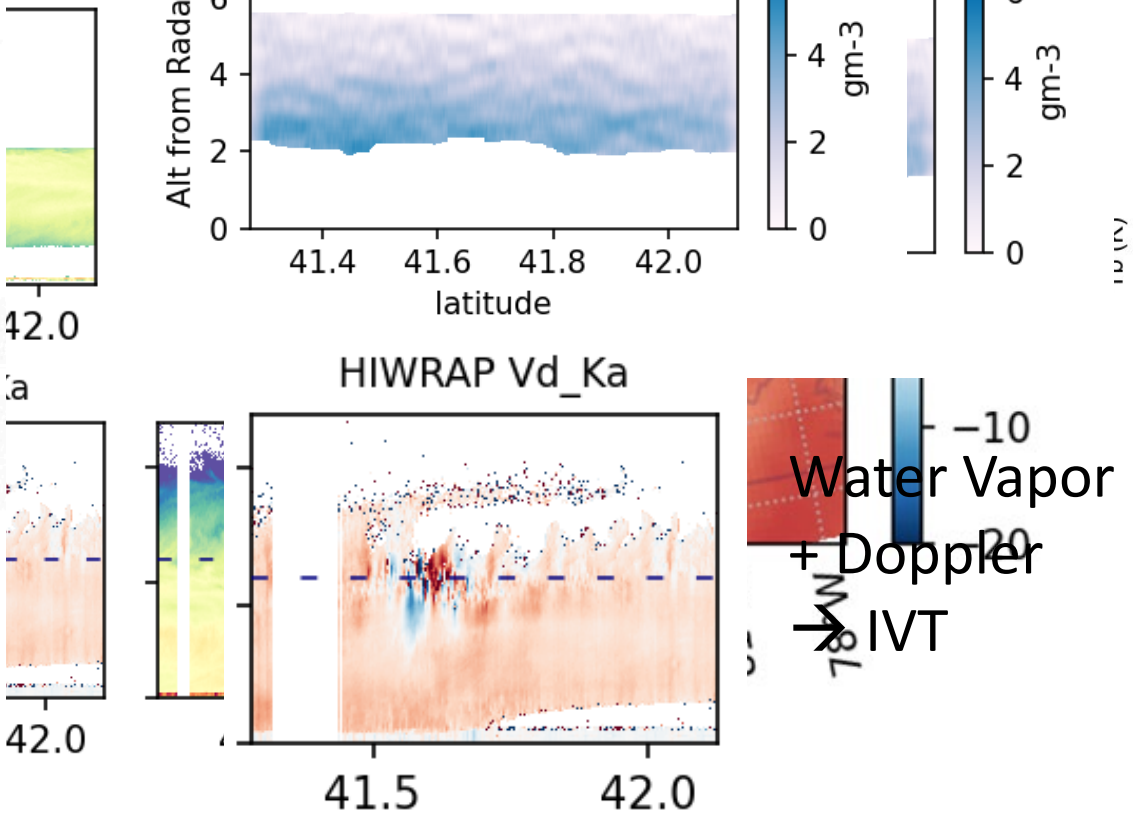


JPL Multi-Frequency Radar in AR Recon

Julia Shates, CW3E

- We are actively pursuing inclusion of JPL's radar in AR Recon
- Illustration from IMPACTS 17 Feb 2022





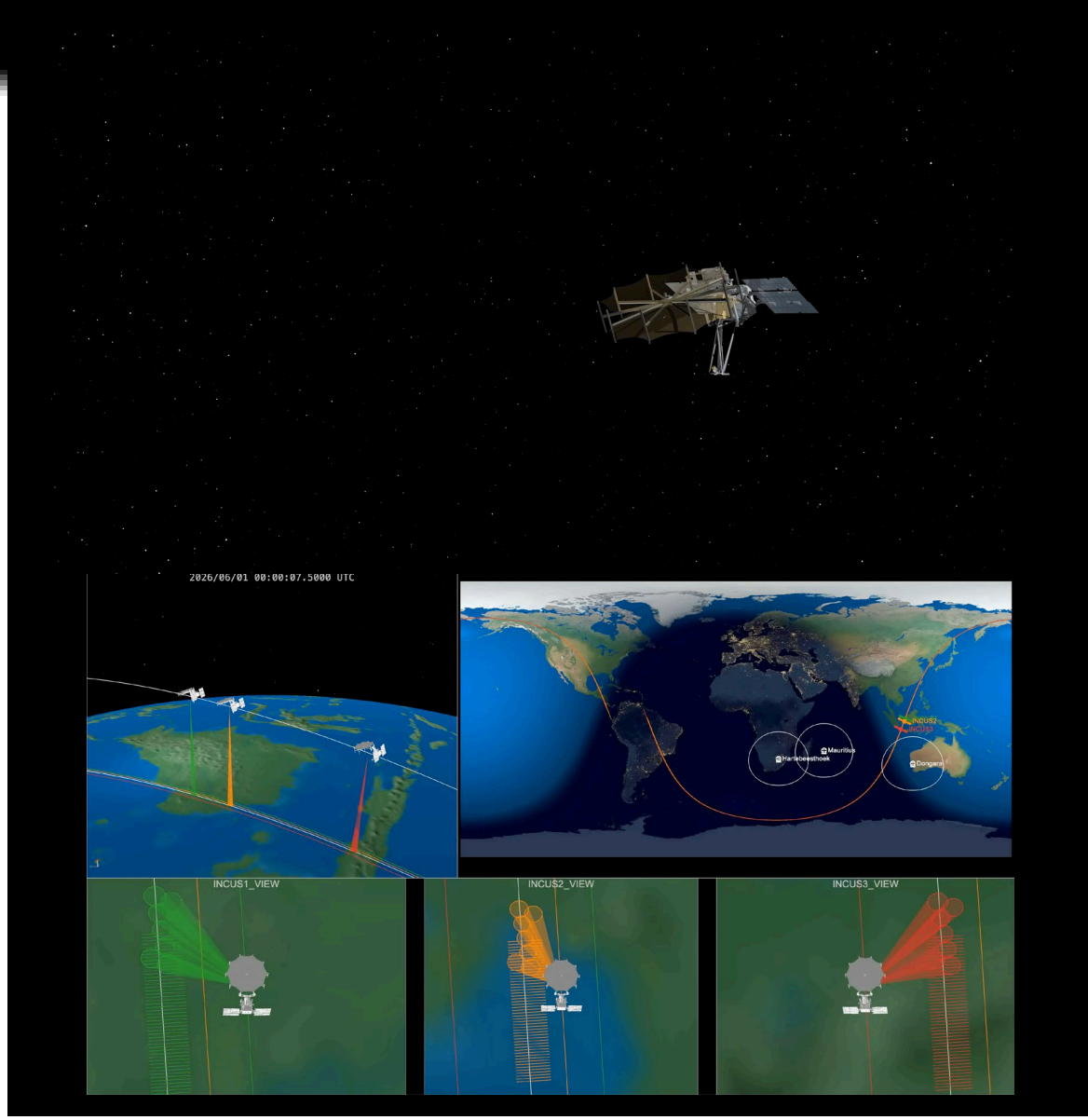
Next Generation Dynamics-Focused Satellite Observations

NASA

- INCUS (2027): vertical motions within cloudy and precipitating regions
- FALCON Radar (2030): Doppler radar in 0930 am/pm orbit
- GPM follow-on expected to include Doppler (2030s)

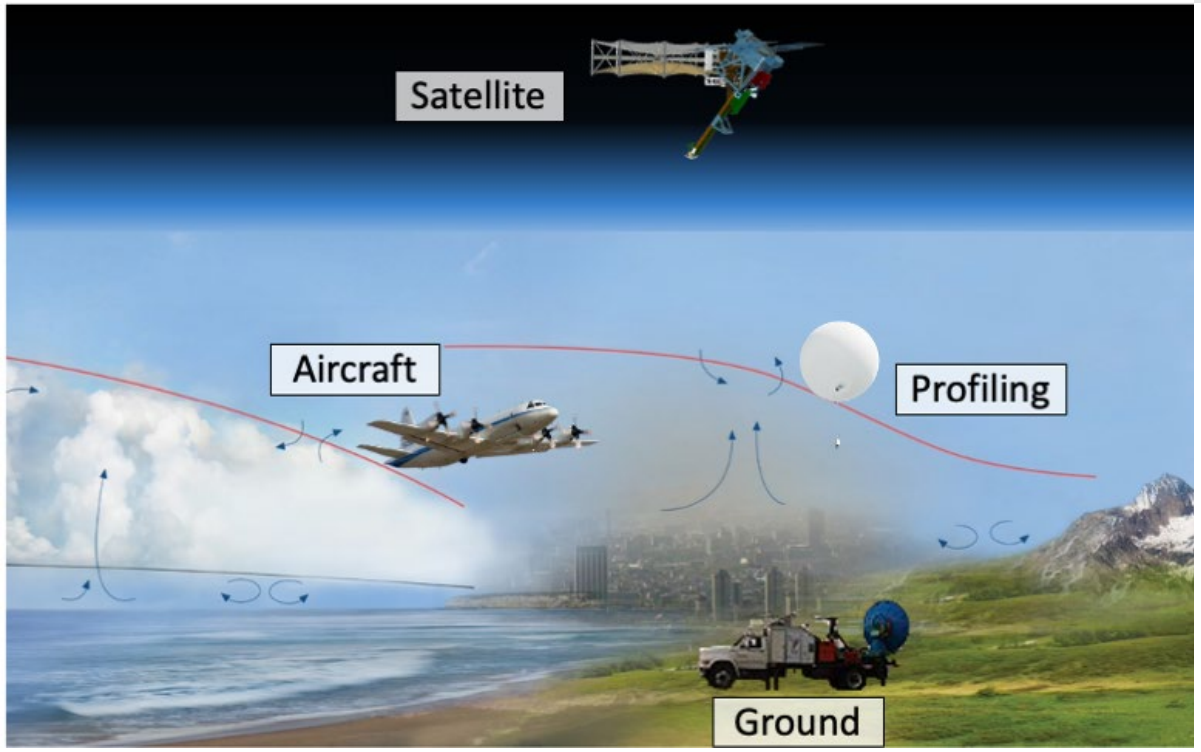
ESA/EUMETSAT

- WIVERN (2030s): scanning Doppler radar
- MTG (current): hyperspectral IR sounding from geostationary



Coordinated Space+Airborne+Ground

- AR Recon has demonstrated the value of coordinated global airborne and surface based observations
- NASA is likely to implement routine airborne observations as part of future mission operations, especially for PBL
- Emerging automated space-based adaptive observing and continuing advances in uncrewed airborne systems provide new opportunities to target specific regions, times, and processes



Depiction of the diverse processes and features in the atmospheric planetary boundary layer, alongside a selection of measurement types and platforms. Adapted from the PBL Study Team Report (Teixeira et al., 2021)

https://science.nasa.gov/earth-science/decadal-surveys/decadal-pbl/

Summary:

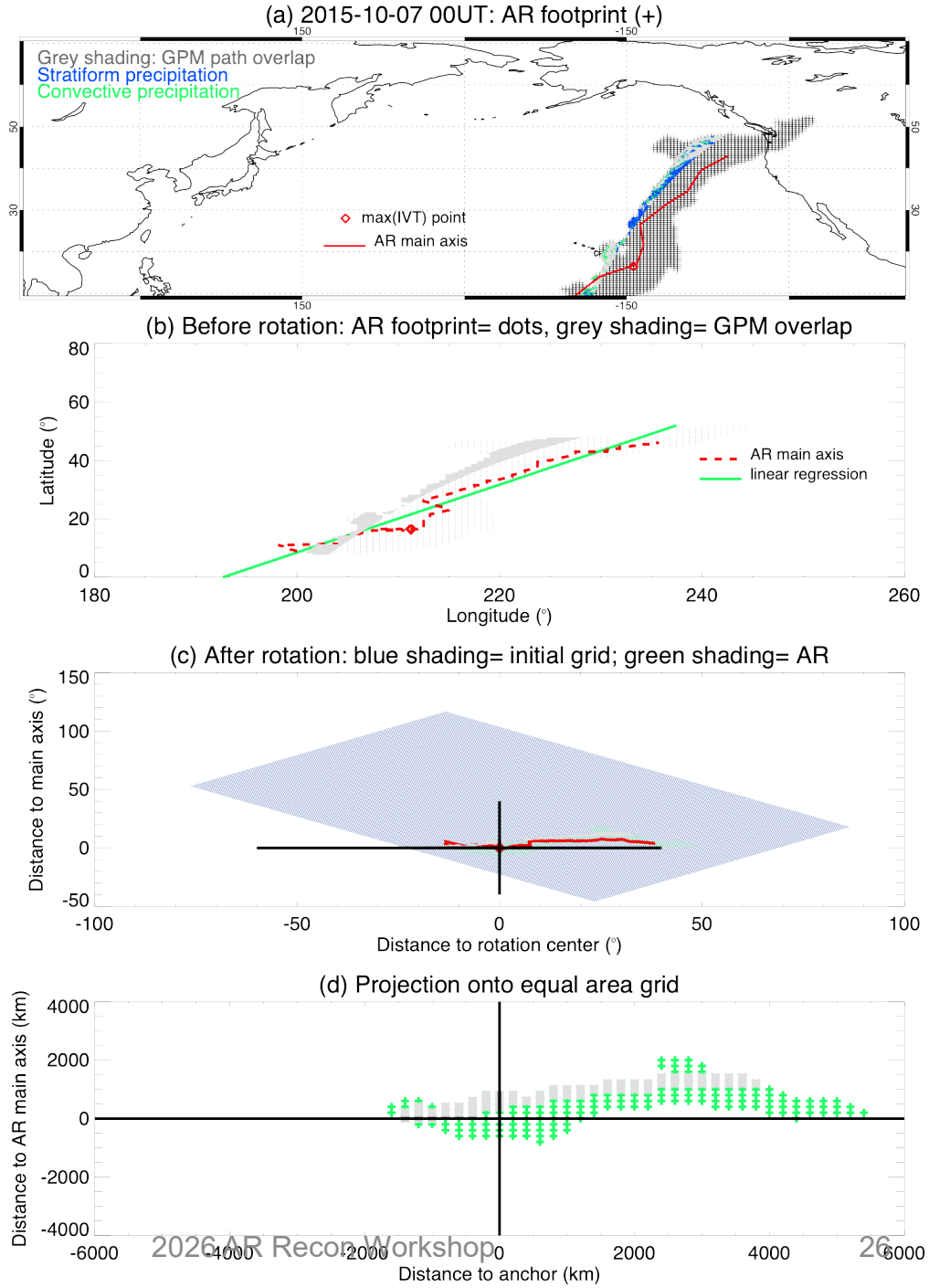
- Nearly 2 decades of satellite based extratropical cyclone and (more recently) AR analysis have revealed
  - Cloud structures and precipitation rates in ARs, ETCs, and fronts
  - How these change with AR strength and environment
  - The potential role of convection in AR development and evolution
- Including airborne radars in AR Recon could illuminate vertical structure and dynamics
- New missions (INCUS, FALCON, PMM, WIVERN) will reveal the dynamics of storms while also observing cloud and precipitation vertical structure

Backup Slides

Compositing method: example

Illustration of various steps for compositing. (a) AR footprint (+) on 2015-10-07 00UT with main axis (red solid), point of maximum IVT (red diamond), and GPM path overlap (grey shading), with locations of stratiform (blue) and convective (green) precipitation. (b) corresponding footprint in latitude-longitude grid, (c) same after rotation of axis the point of maximum IVT to align a linear regression (green) of the main AR axis (red) along the horizontal. (d) AR footprint (green) and GPM overlap (grey) after rotation and projection onto an equal area grid of 200 km resolution centered on the point of maximum IVT.

In this example, the point of maximum IVT occurs towards the tail end of the AR, presumably because integrated moisture is larger towards the equator



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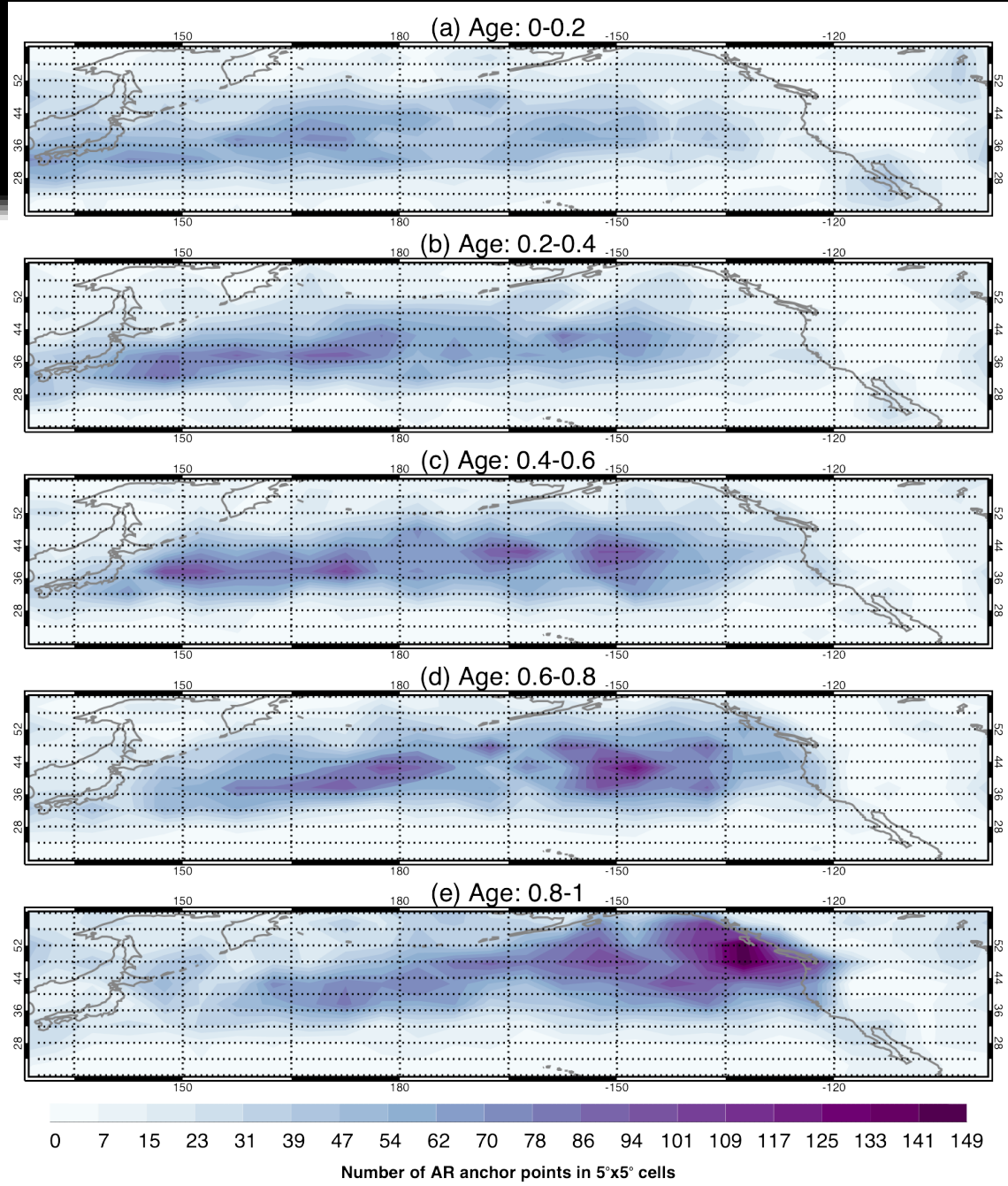
AR Life Stages

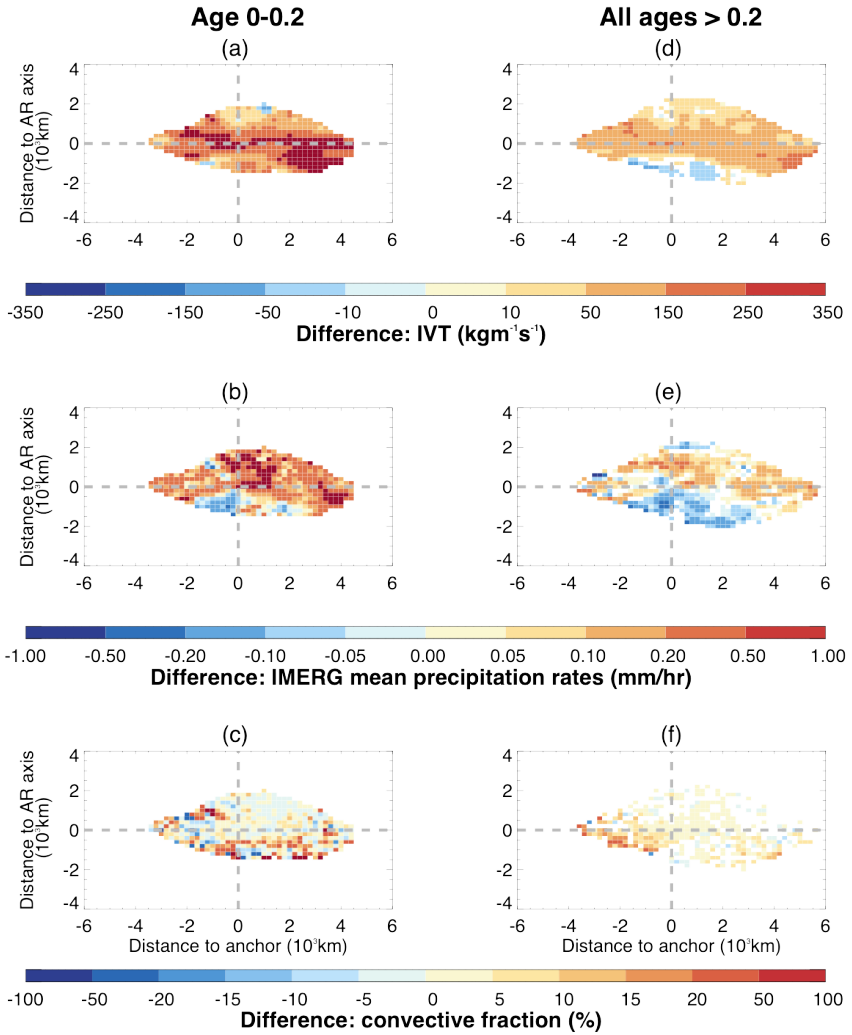
- Partition the ARs into 5 age group bins of size 0.2, i.e. 0.0-0.2 to 0.8-1.0.
- The location of the ARs per age group follows the storm track of ETCs typical of the north Pacific



IVT and Precip vs AR Life Stage – Early vs Late

Catherine Naud, Columbia University

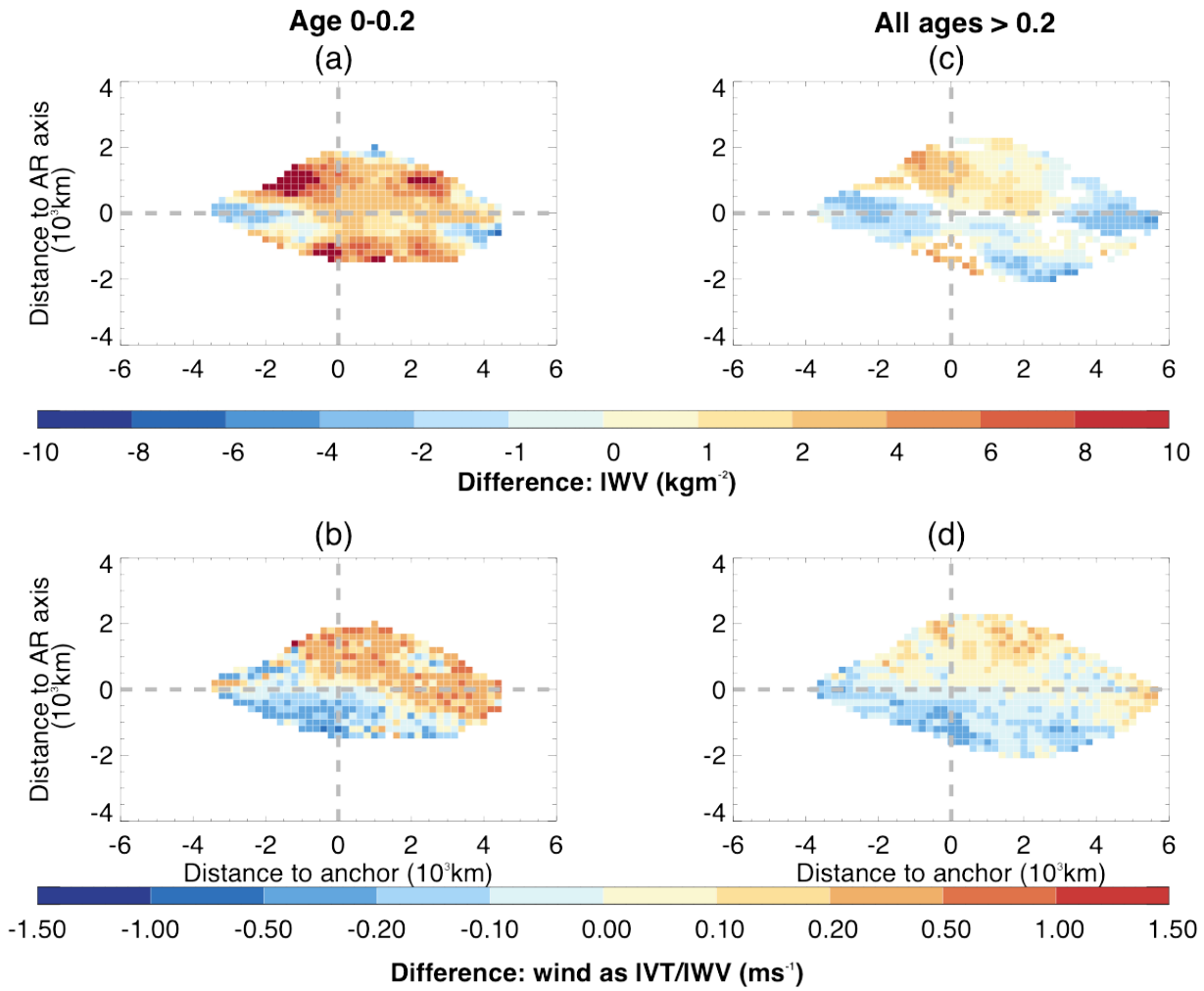
- Separate dataset into 1/3's by **IVT**
- Subtract composite fields for lowest 33% IVT from those with highest 33% IVT
- Again, patterns of IVT and mean precipitation match
- There is no clear relationship between the pattern of convective fraction and the pattern of mean precipitation and IVT



Convective Precip vs AR Life Stage

Catherine Naud, Columbia University

- IVT differences – due to larger water vapor or larger winds?
- Separate the integrated water vapor (IWV) component of IVT, from the wind component (ratio of IVT and IWV).
- Examine the IWV and wind differences between high and low convective activity ARs.
- At age 0.0-0.2, IWV is larger in high convective fraction ARs across most of the AR region
- As these ARs mature, IWV remains larger in the east-poleward quadrant where precipitation is larger in high convective cases.
- Contrasts between high and low convection cases in wind are larger in the eastern half mostly, especially in the poleward, high precipitation rate, quadrant for young and mature ARs.
- Any dynamical impact of convection on the ARs occurs in the high precipitation rates quadrant.



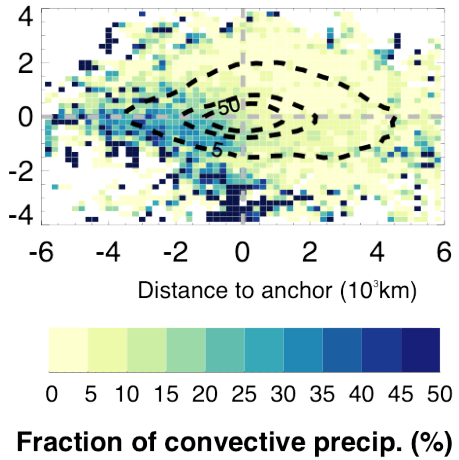
Convective Precip vs AR Life Stage

Catherine Naud, Columbia University

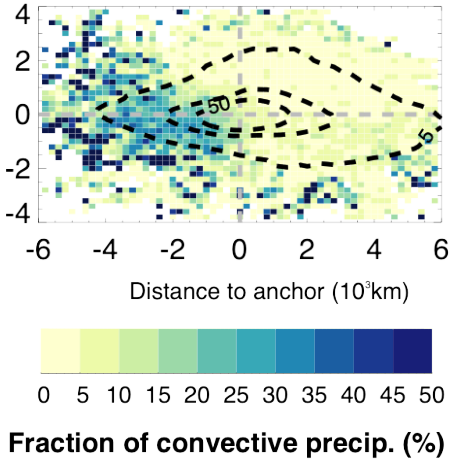
Normalize each AR life cycle into
5 stages from initial to final detection

The signal is subtle, but there is a systematic decrease in convective precip with AR age

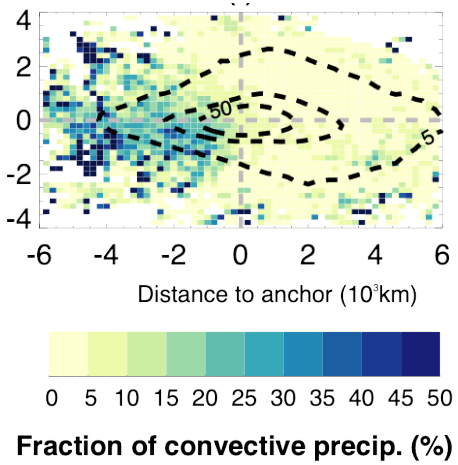
Stage 0



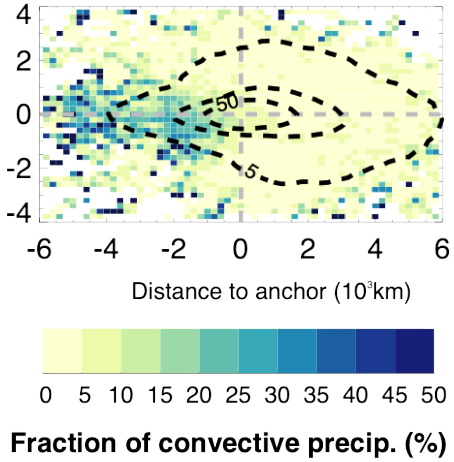
Stage 1



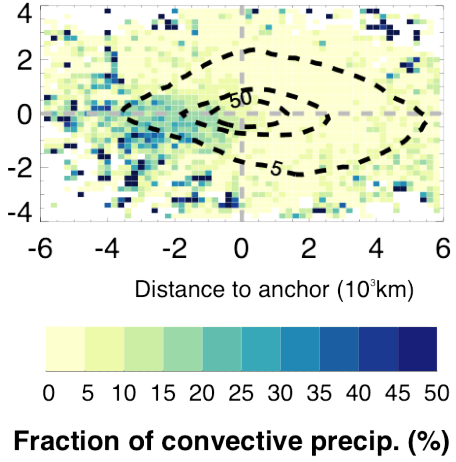
Stage 2

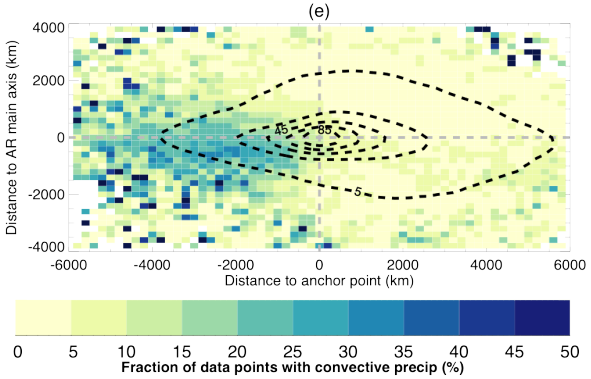


Stage 3



Stage 4





% of GPM P>0 data points with convective precipitation

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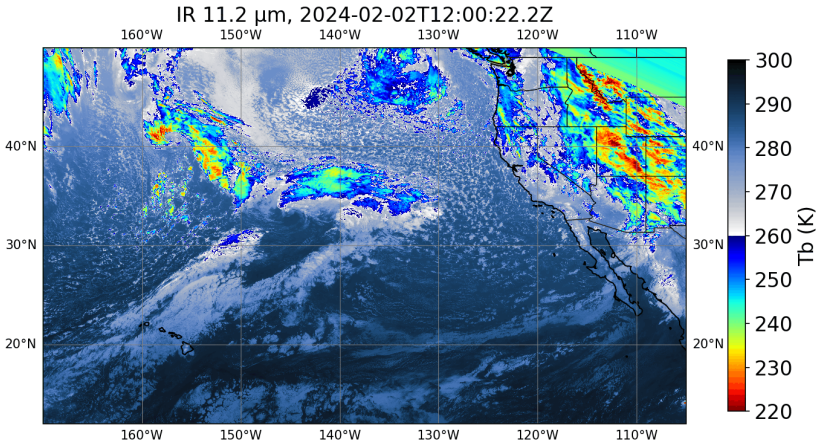
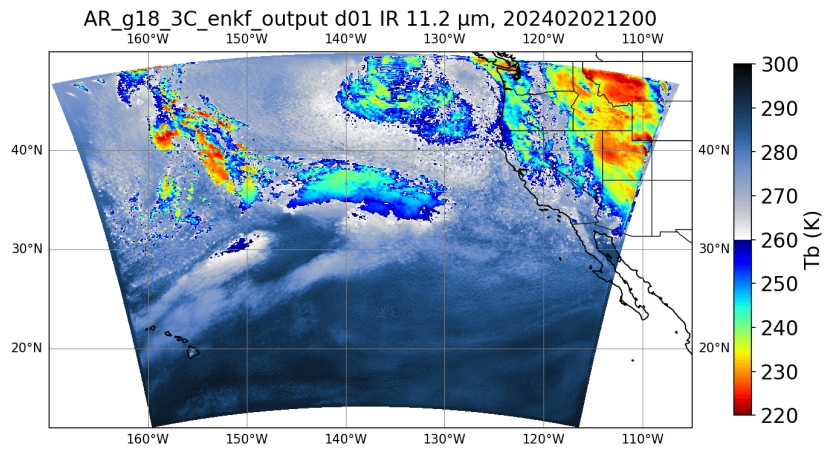
Promise of High Resolution All-Sky DA

- We tend to rely on reanalysis as “truth”
- Current resolution is limited
- Results are affected by model parameterizations
- High resolution DA has promise for extracting additional process information at fine scales

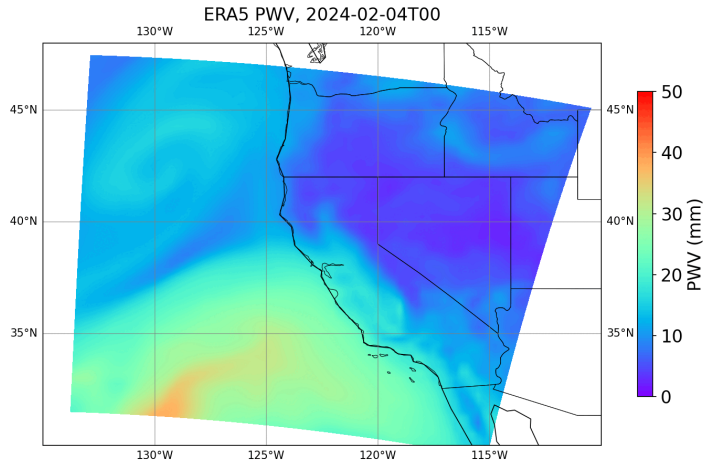
Geostationary IR



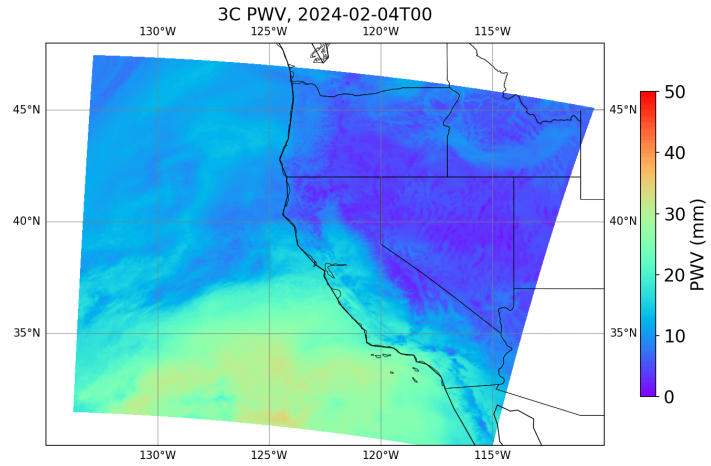
EnKF Analysis



ERA-5

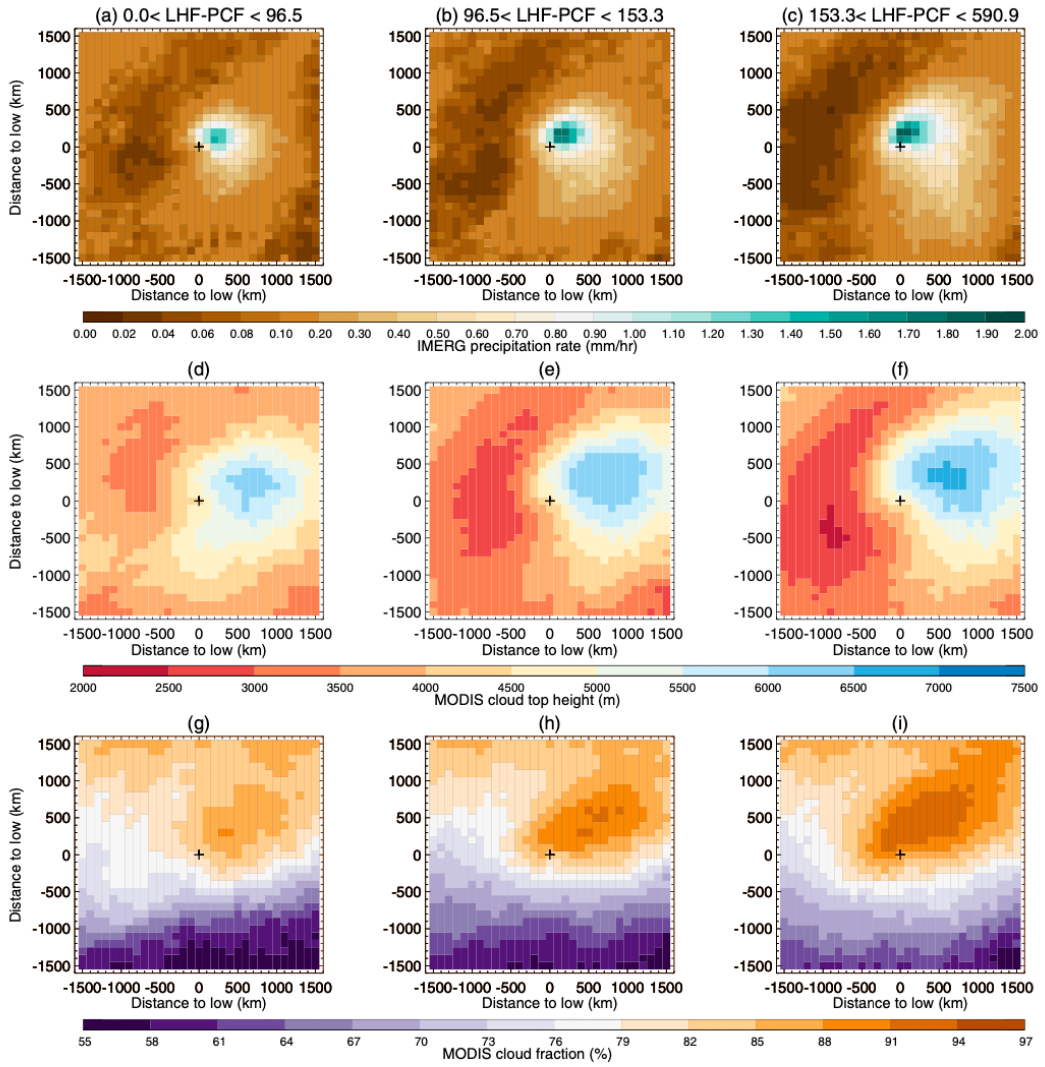


EnKF Analysis



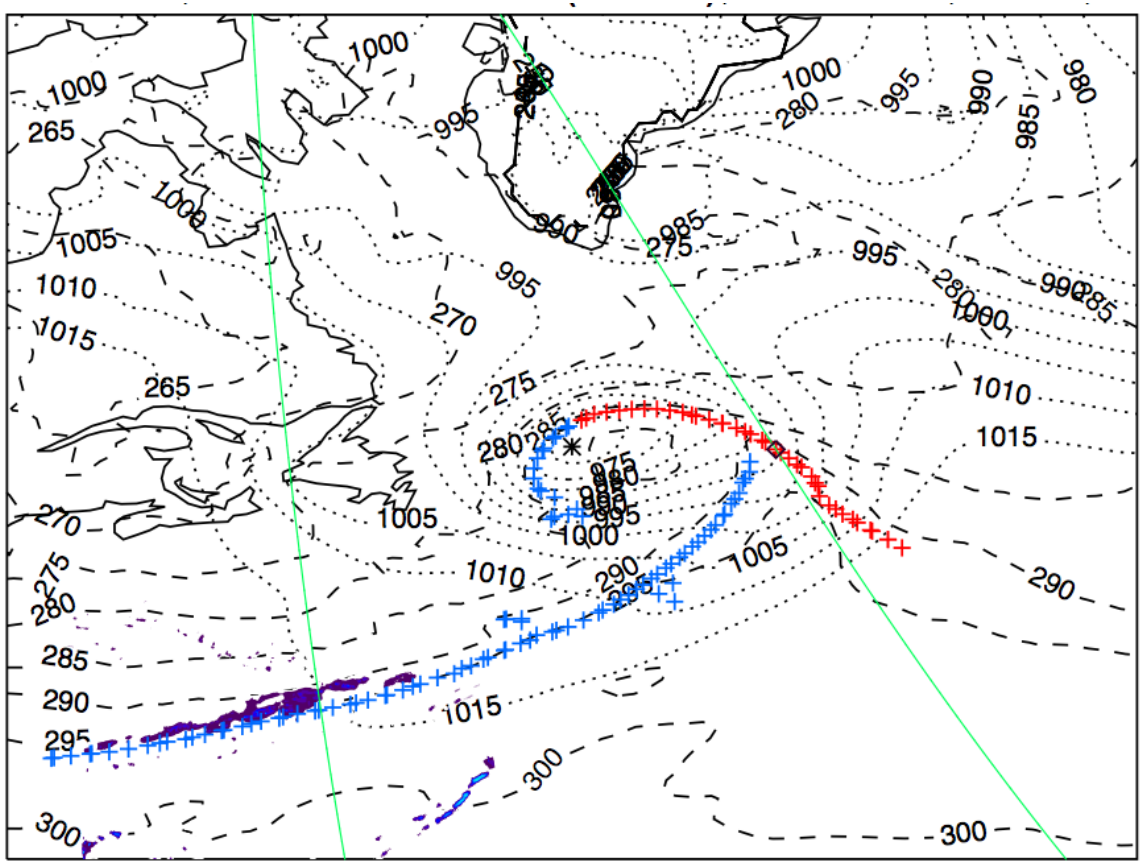
Relationship Between Surface Fluxes and ETC Clouds and Precipitation (Naud et al. (2023)

- Composite cloud fraction, cloud top height, and precipitation rate as a function of surface latent heat fluxes
- Storm precipitation rate, cloud top height, and cloud fraction increase with increasing ocean surface latent heat flux.



Extratropical Cyclones: Warm and Cold Fronts
Naud et al. (2012; 2015, J. Climate)

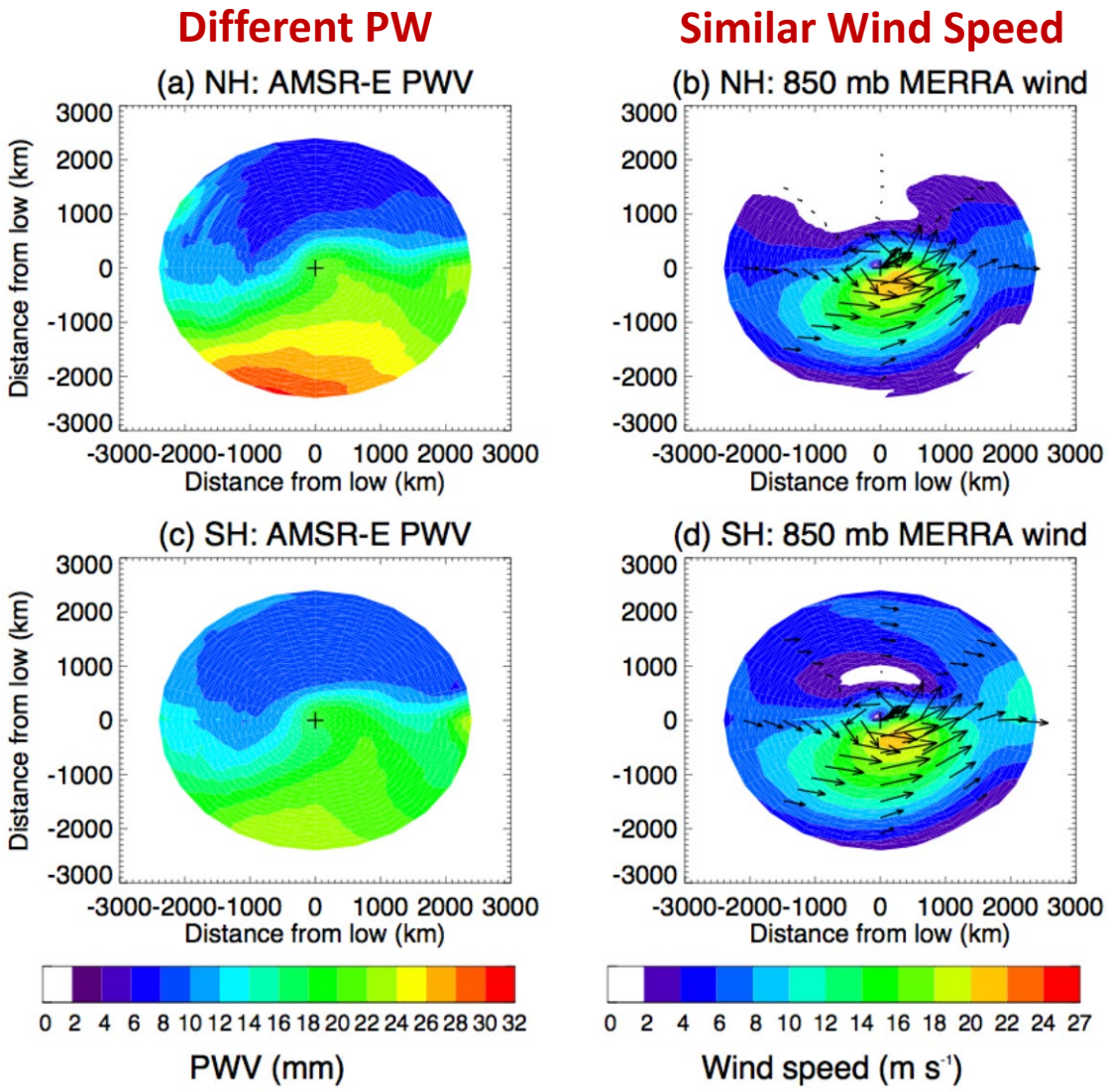
- Satellite based composite study of warm fronts reveals hemispheric differences in cloud and precipitation
- Distinction appears to be related to changes in the cyclone environment
- Questions:
  - Differences in cloud distribution between warm and cold fronts?
  - How does the distribution of cloud types change with changes in the environment?
- Examine composites of cold fronts from CloudSat



North Atlantic, 1800 UTC 5 December 2006

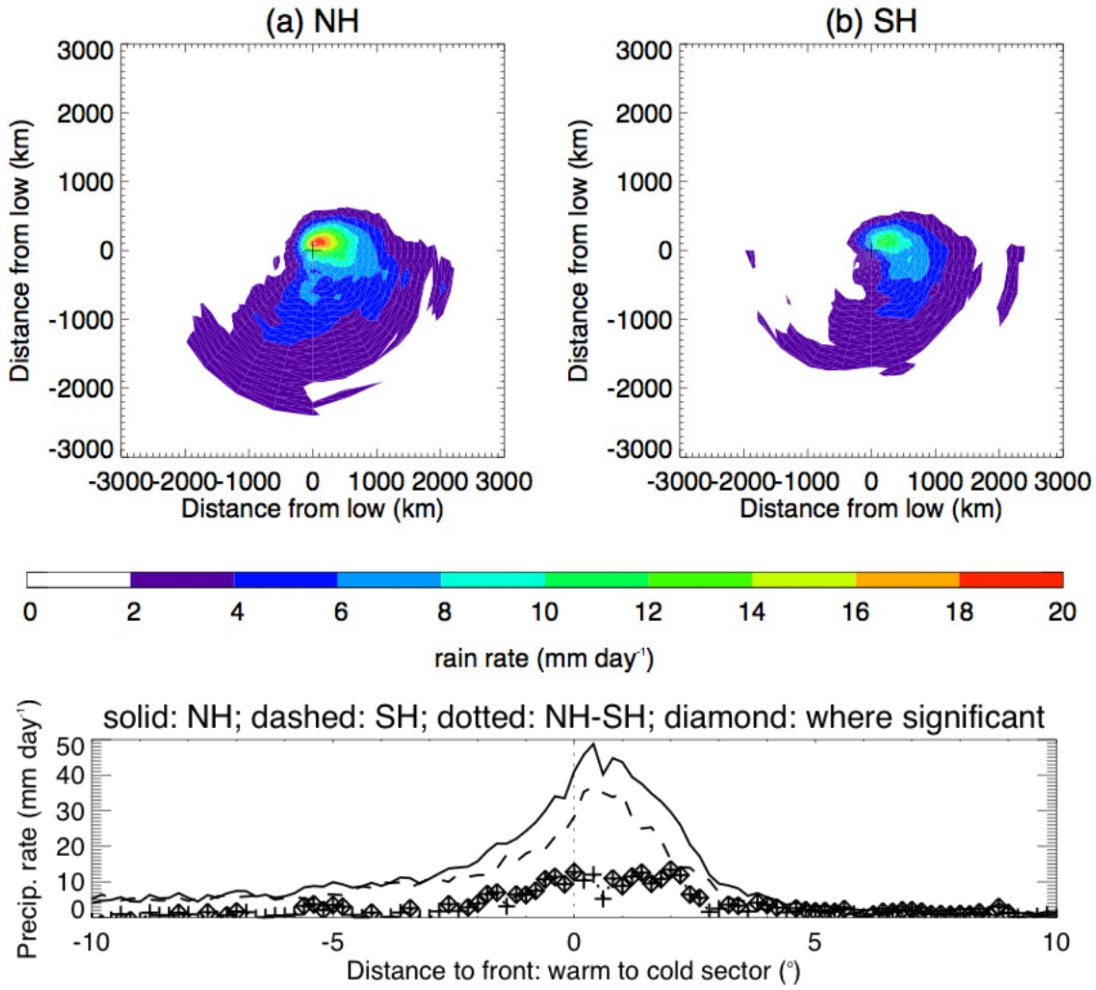
Extratropical Cyclones: Warm Fronts
(Naud et al., 2012, J. Climate)

- Examine warm fronts and the associated warm conveyor belt circulation
- Explore sensitivity of frontal structures to changes in the environment
- Determine whether systematic differences exist between hemispheres



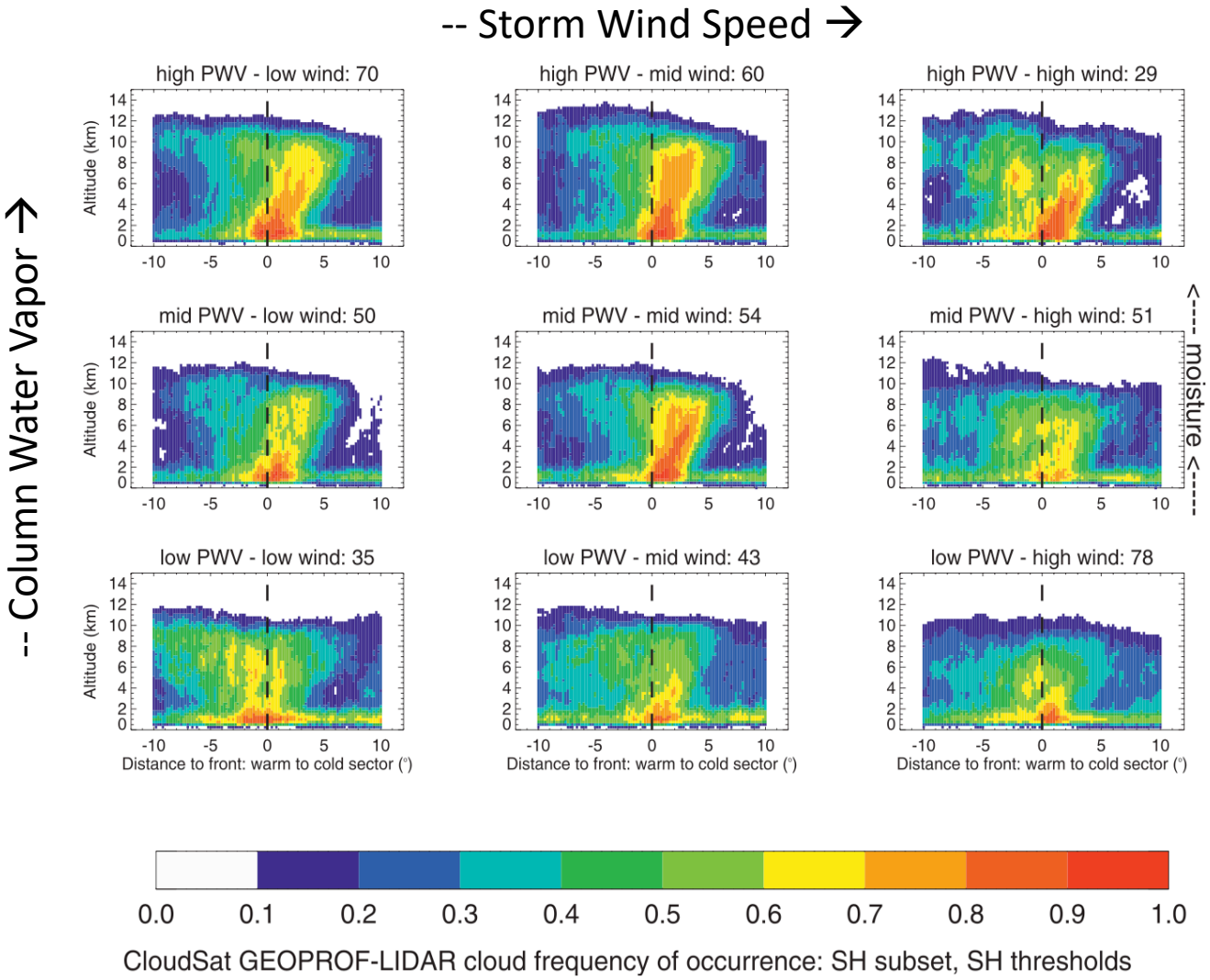
Extratropical Cyclones: Warm Fronts
(Naud et al., 2012, J. Climate)

- Precipitation rates are higher in the northern hemisphere than in the south.
- What is the effect of a change in the amount of precipitable water?



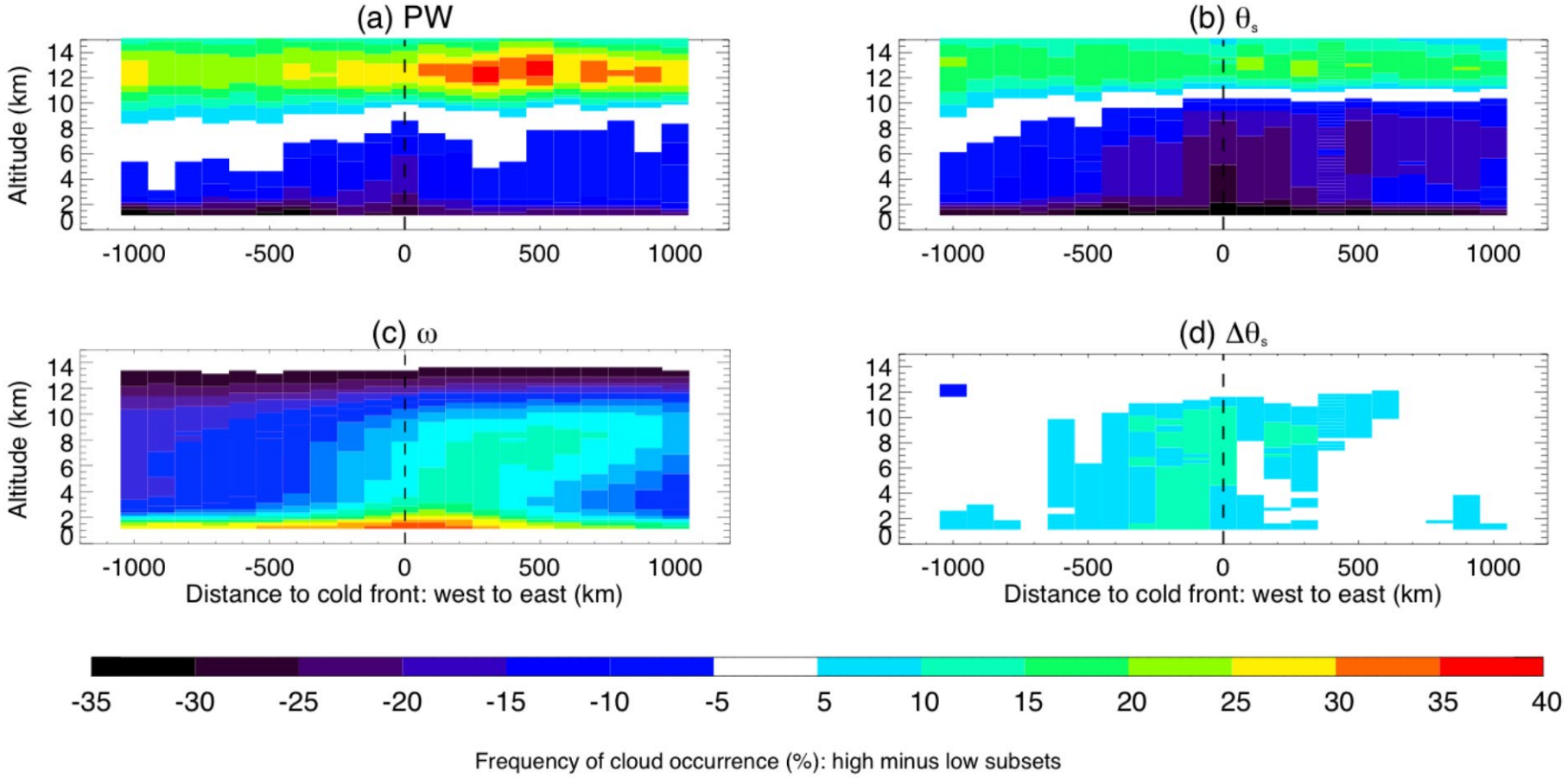
Extratropical Cyclones: Warm Fronts
(Naud et al., 2012, J. Climate)

- Examine changes in cloud distribution with changes in storm strength and water vapor content
- Southern hemisphere storms appear to be susceptible to changes in water vapor



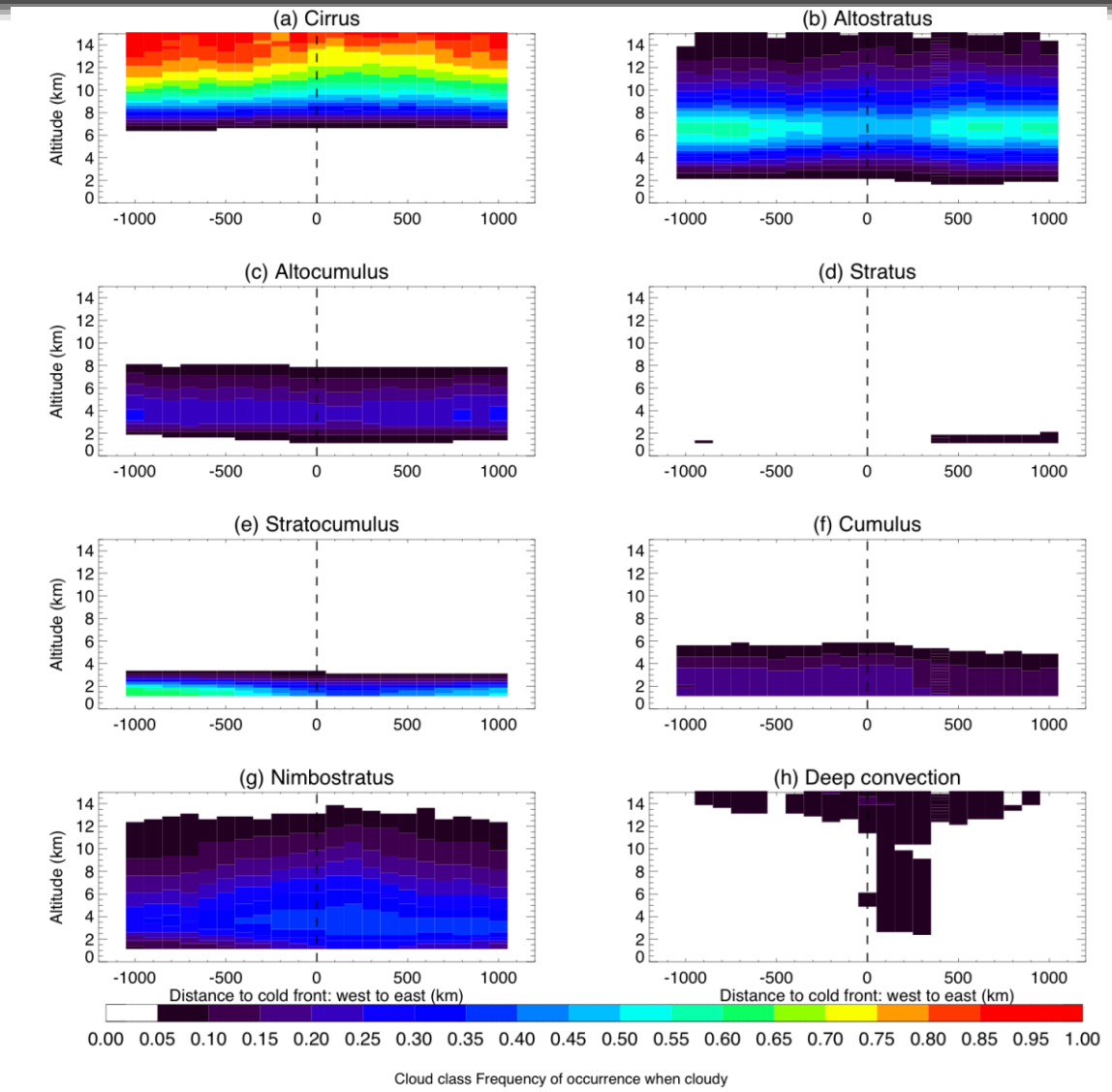
Extratropical Cyclones: Cold Fronts
(Naud et al., 2015, J. Climate)

- Cloud fraction differences in different storm states
- Difference cloud fraction in lowest 10% from cloud fraction in highest 10%



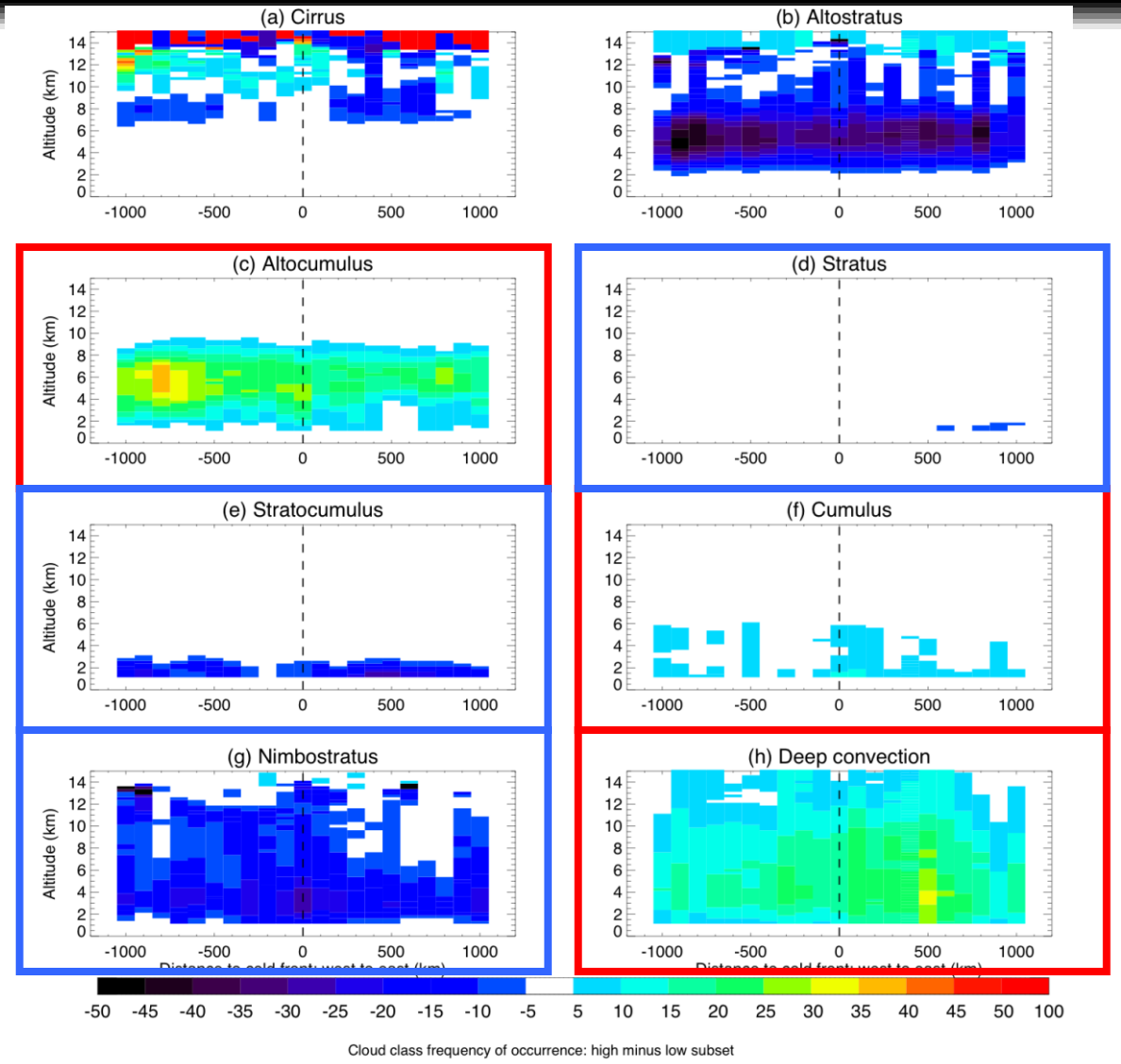
Extratropical Cyclones: Cold Fronts
(Naud et al., 2015, J. Climate)

- Examine the occurrence of different cloud types across cold fronts
- Increased incidence of deep convection and nimbostratus ahead of the front
- Increased incidence of cumulus and stratocumulus behind
- How do clouds change with environment?



Extratropical Cyclones: Cold Fronts (Naud et al., 2015, J. Climate)

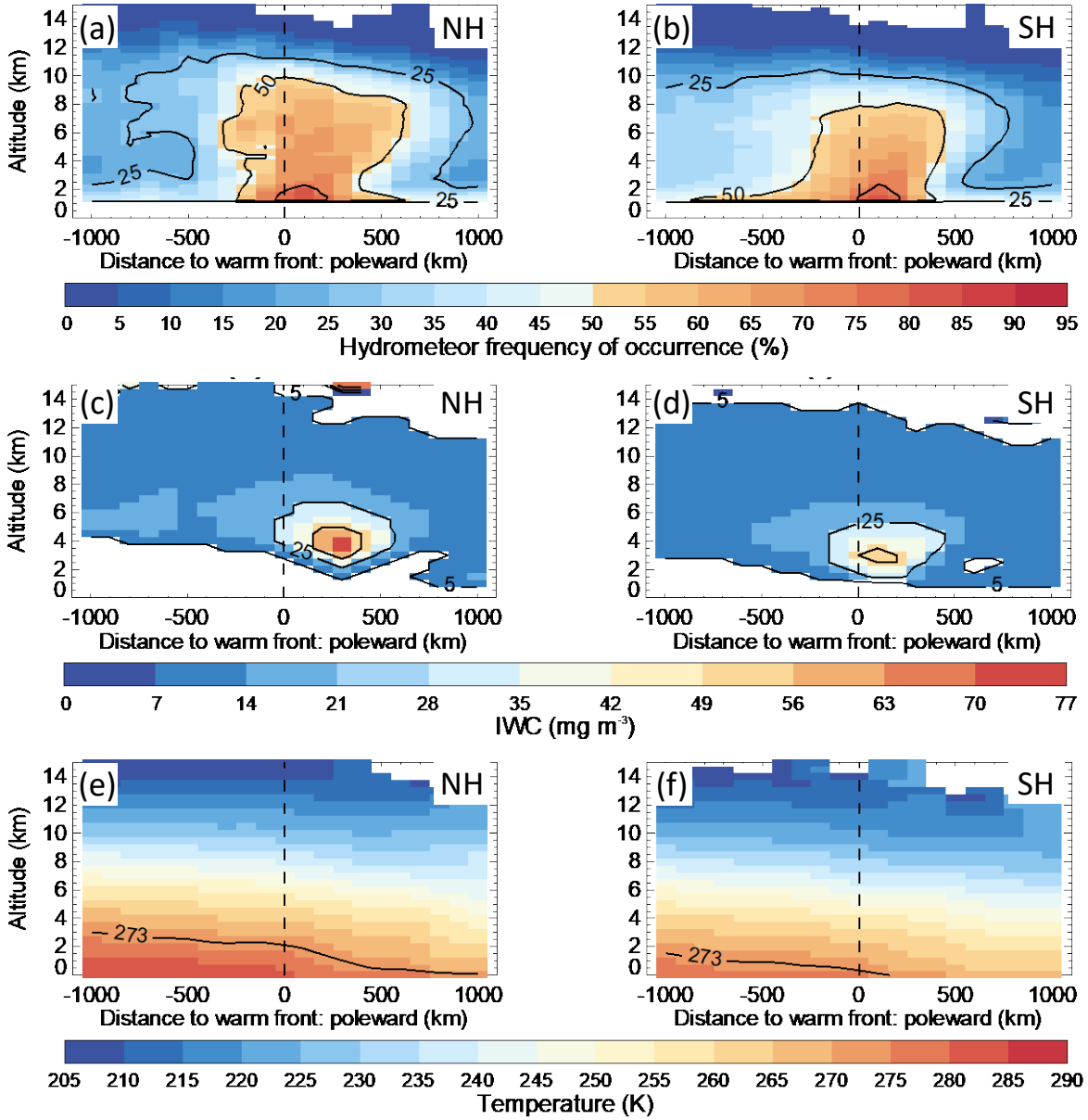
- Examine how cloud types change with environmental water vapor
- Difference cloud types for **wettest** 10% and **driest** 10% of all fronts
- Systematic **increase** in deep convection, cumulus, and altocumulus
- Systematic **decrease** in nimbostratus and altostratus
- **Change in convective cloud fraction in a moistening (warming) environment**



Changes in Ice Content?

Takahashi et al. (2024)

- Fronts in the northern hemisphere have deeper clouds with larger ice water content than those in the southern hemisphere.



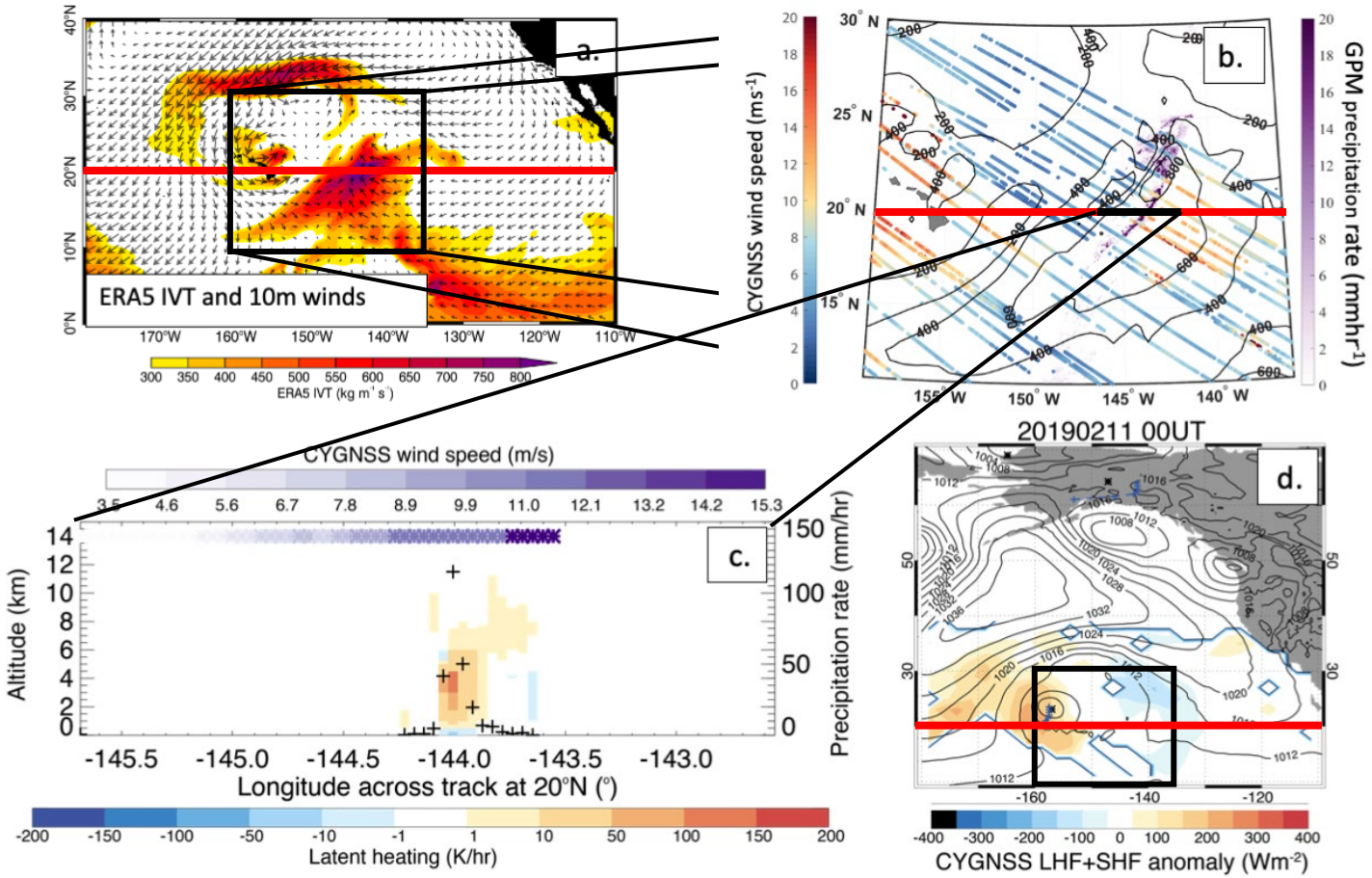
Models as a Laboratory to Explore Processes (Rosa Luna Niño)

- UCSD Scripps CW3E has run large ensembles of AR simulations
- Perturbed initial conditions and parameterizations
- Utilize these ensembles + observational analysis to learn about the role of cloud and PBL processes in AR formation, evolution, and outcomes

Group	Convective Scheme	Microphysics Scheme	PBL Scheme
GTA	Grell	Thompson	Acm2
GMA	Grell	Morrison	Acm2
GTY	Grell	Thompson	YSU
GMY	Grell	Morrison	YSU
TTA	Tiedke	Thompson	Acm2
TMA	Tiedke	Morrison	Acm2
TTY	Tiedke	Thompson	YSU
TMY	Tiedke	Morrison	YSU

GPM + CYGNSS Observations of Atmospheric Rivers: Surface Fluxes + Latent Heating

- Current project uses PMM + CYGNSS data
- Examine relationships among:
  - Surface fluxes
  - Atmospheric river vapor transport
  - Precipitation
  - Latent heating



(a) Reanalysis IVT (shaded)
(b) Surface precipitation (shaded, purple) and winds (blue-red)
(c) Latent heating profiles (color fill), precipitation (+), and winds (purple)
(d) Ocean surface flux anomalies (shaded blue-red)

Methodology, input, technique

- Use AR database from Guan-Waliser applied to MERRA2 of v4:
  - footprint of AR (lat/long/time)
  - location of main axis of AR
  - normalized age (number from 0 to 1).
- Period: 2015-2024
- Observations: (~43,000 ARs with GPM overpass)
  - GPM-CMB for (near) surface precipitation rates and stratiform/convective type flag (DPR), L2 along track data (245 km wide swaths) acquired within ±6hrs of AR identification
  - IMERG (final run), to get full coverage of surface precipitation using time step closest to AR identification time
- Other data: from MERRA2 use IVT and 500 hPa vertical velocity fields
- For each set (GPM & MERRA2),
  1) extract data in AR footprint.
  2) apply rotation and regridding for each AR => equal area grid of 200 km spatial resolution based on distance to anchor
  3) composite data (mean, median) for all or subsets of AR using the same anchor and main direction axis
- **Anchor: point with max(IVT) in AR**