Clouds and Precipitation in GCM Extratropical Cyclones: An Analysis Based On Cyclone-Centered Metrics

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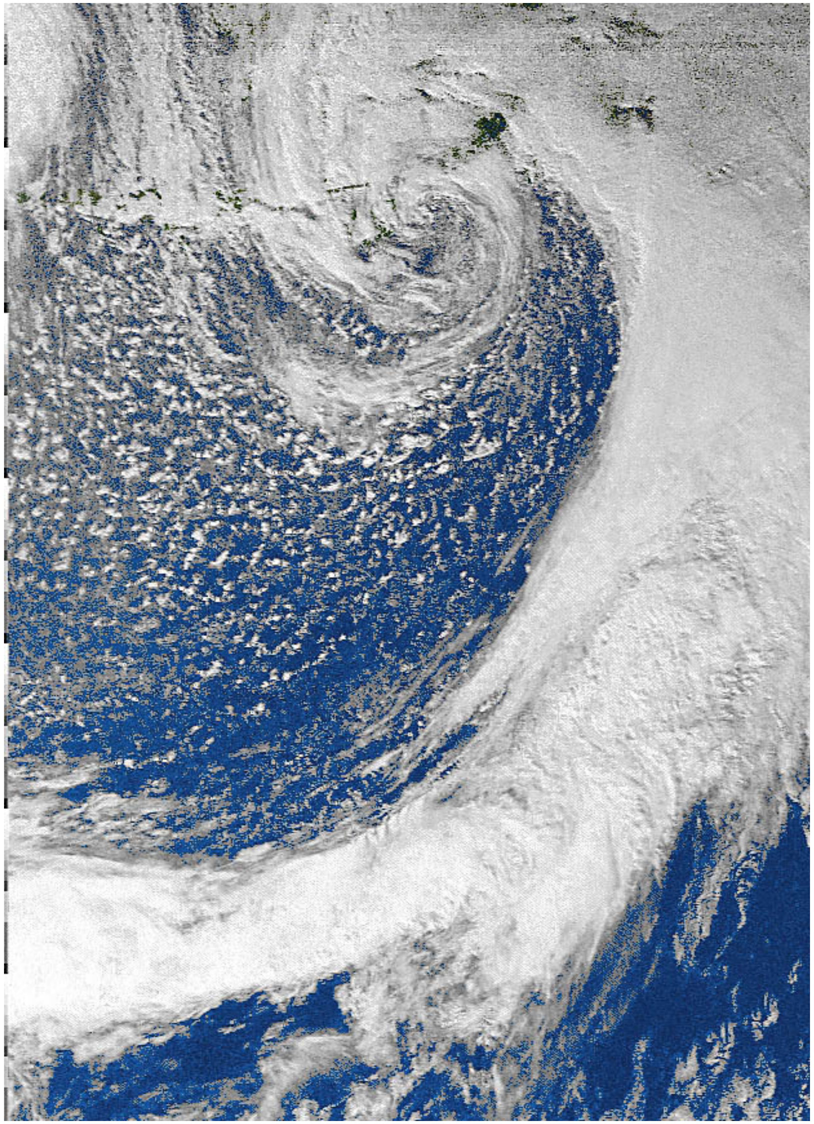


Research funded in part by NOAA Climate Program Office's Modeling, Analysis, Predictions, and Projections program

NOAA
Model Diagnostics Task Force (MDTF)
Diagnostics Package

MOTIVATION

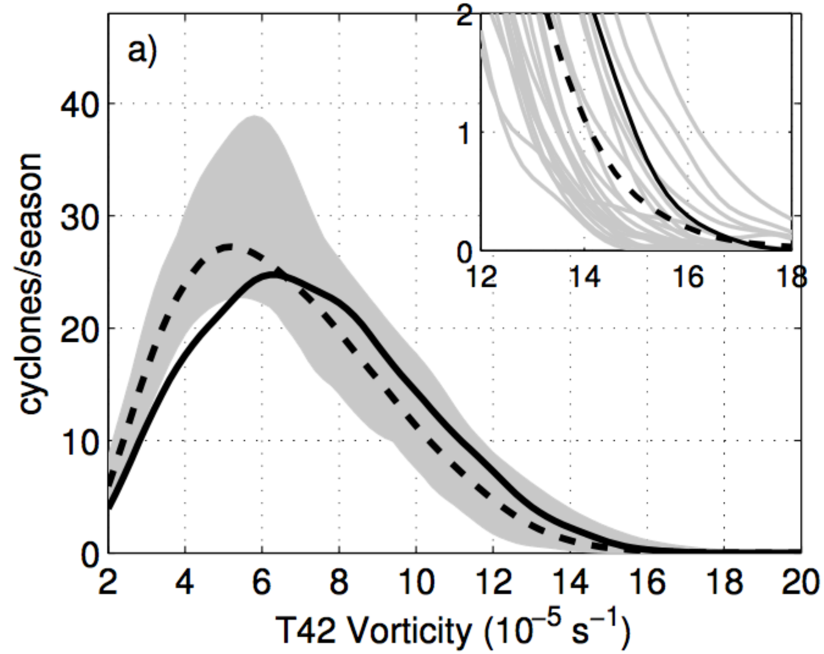
1. GCMs have too few midlatitude clouds in the southern hemisphere.
   - associated with extratropical cyclones. Bodas-Salcedo et al., 2014, JCLIM

2. Extratropical cyclone intensity distribution: too much towards weaker storms and missing the strongest storms.

3. Latent heating within storms:
   - impacts storm strength
   - directly associated with precip

4. Parameterized convection can impact the vertical advection of moisture in the warm conveyor belt. (Boutle et al. 2011, QJRMS).

Storm Strength Distributions CMIP5, DJF



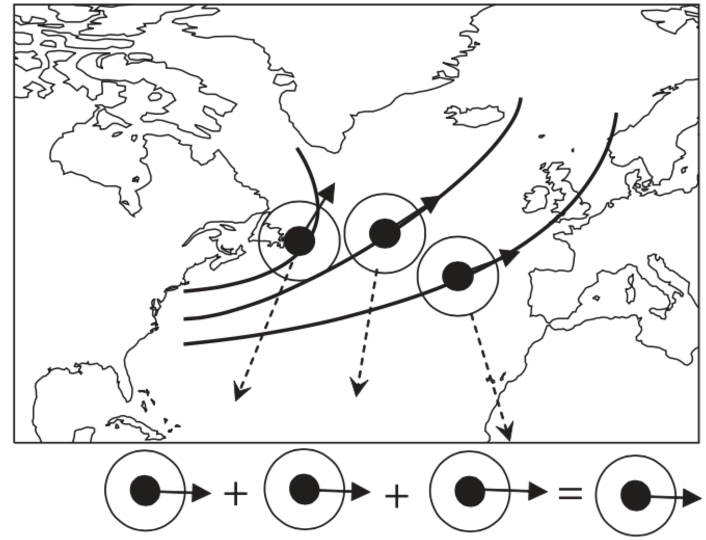
Zappa et al.,2013, JCLIM

METHODS: Cyclone-centered compositing

1. Find cyclones based on central pressure
2. Link cyclones in time to create tracks

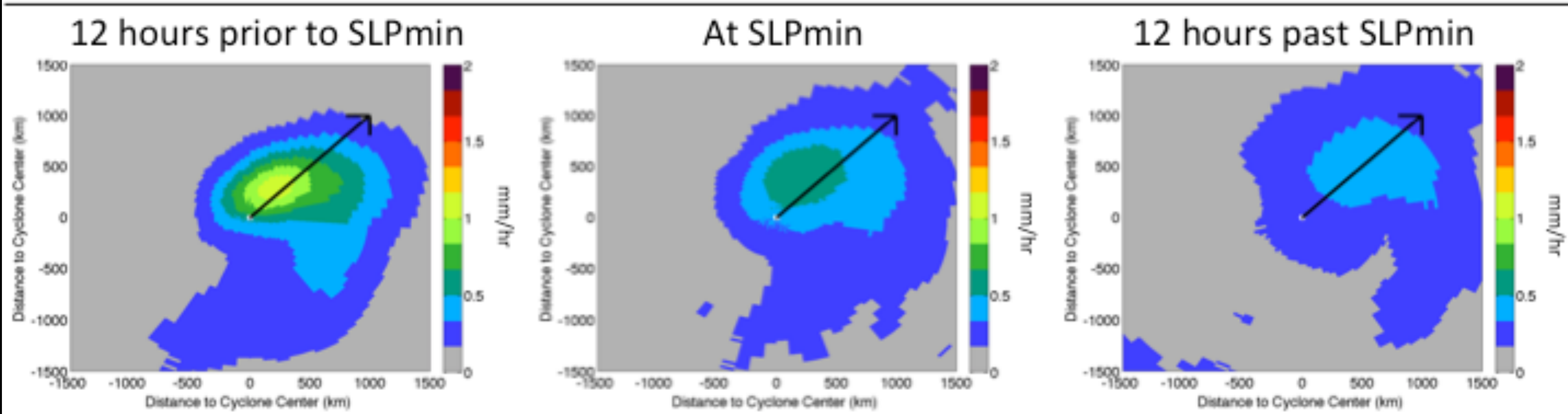
3. Extract data around center of each storm
4. Average multiple cyclone-centered data
5. For SH: flip N/S orientation of the cyclone

6. Examine the precipitation for a specific point in the storm life cycle.



Catto et al. 2010

NORTH ATLANTIC ERAI INTERIM CYCLONE PRECIPITATION (mm/hour)

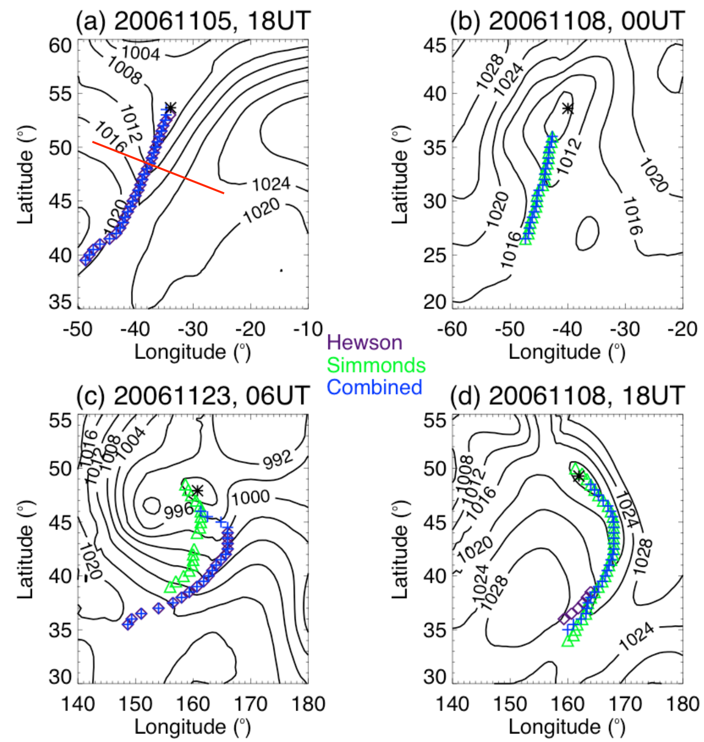


cyclones projected to equal area stereographic grid and rotated, so track direction is 45˚ NE

METHODS: Frontal transects compositing

- Locate cold front with Hewson (1998) and Simmonds et al (2012) methods based on MERRA2 (Naud et al., 2016, JCLI)
- Create a composite using a vertical transect grid, centered along the horizontal on the cold front (±1000km)
- Use CloudSat-CALIPSO profiles, populate grid based on distance to cold fronts, within ±3hrs
- Use cloud mask (GEOPROF-LIDAR) & cloud classification (CLDCLASS-LIDAR)
- For the models, use all grid cells in a rectangle of length the cold front and width 2000 km and average along a perpendicular to the front in 100 km wide columns.

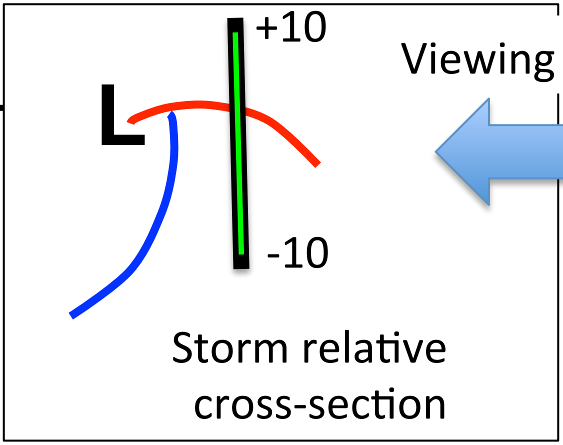
COLD FRONT DETECTION EXAMPLES



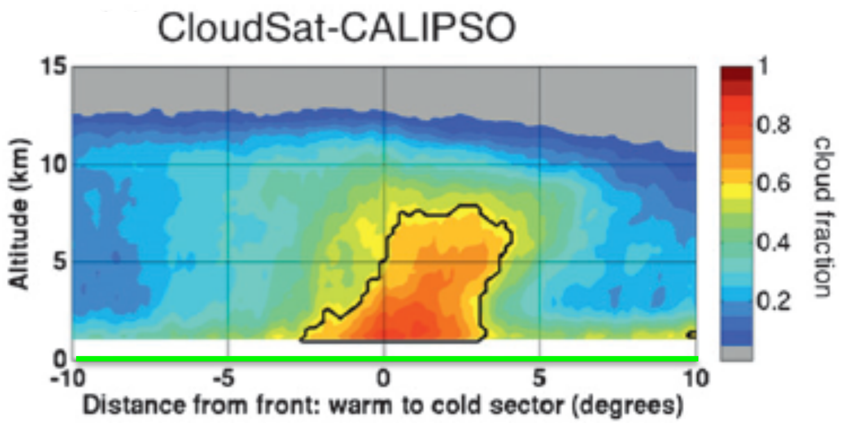
Purple: Hewson method
Green Simmonds et al. method
Blue: Combination
Red line: transect location

MOTIVATION

Parameterized convection can impact clouds within the extratropical cyclones



Booth et al., JCLIM 2013: cyclone-local compositing of CloudSat/CALIPSO and NASA GISS ModelE2

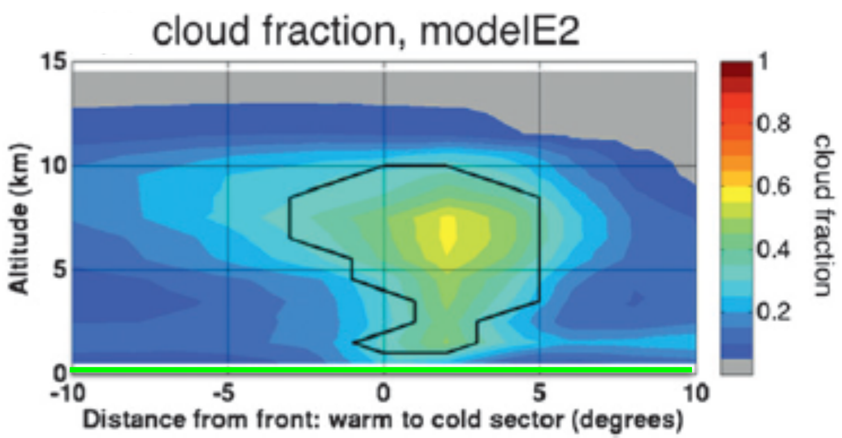


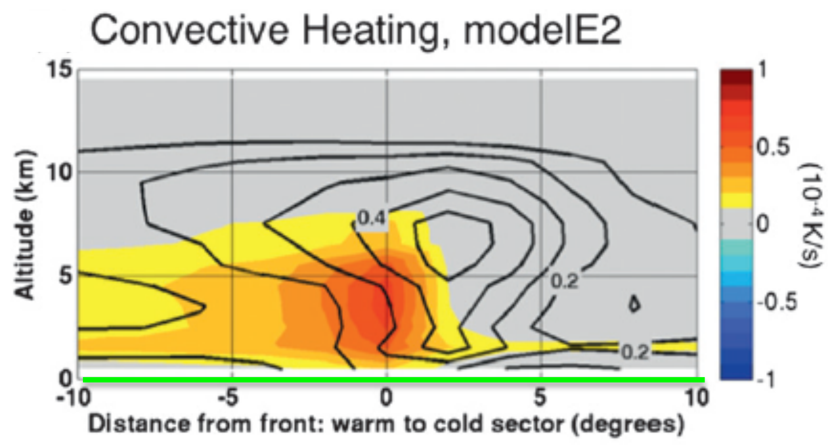
TRANSECTS ACROSS WARM FRONT

Left top: satellite observations

Left bottom: GISS Model

Below: convective heating in the model





Track intensification in GISS GCM biased weak

What precip to use for benchmarking the models?

<u>GPCP</u>: satellite and gauge data.

<u>ERA-Interim</u>: assimilates similar data; relies on model physics to generate precipitation & clouds.

- Agree well on rain location
- ERAI has too much precip in storms over ocean (<u>top row</u>)

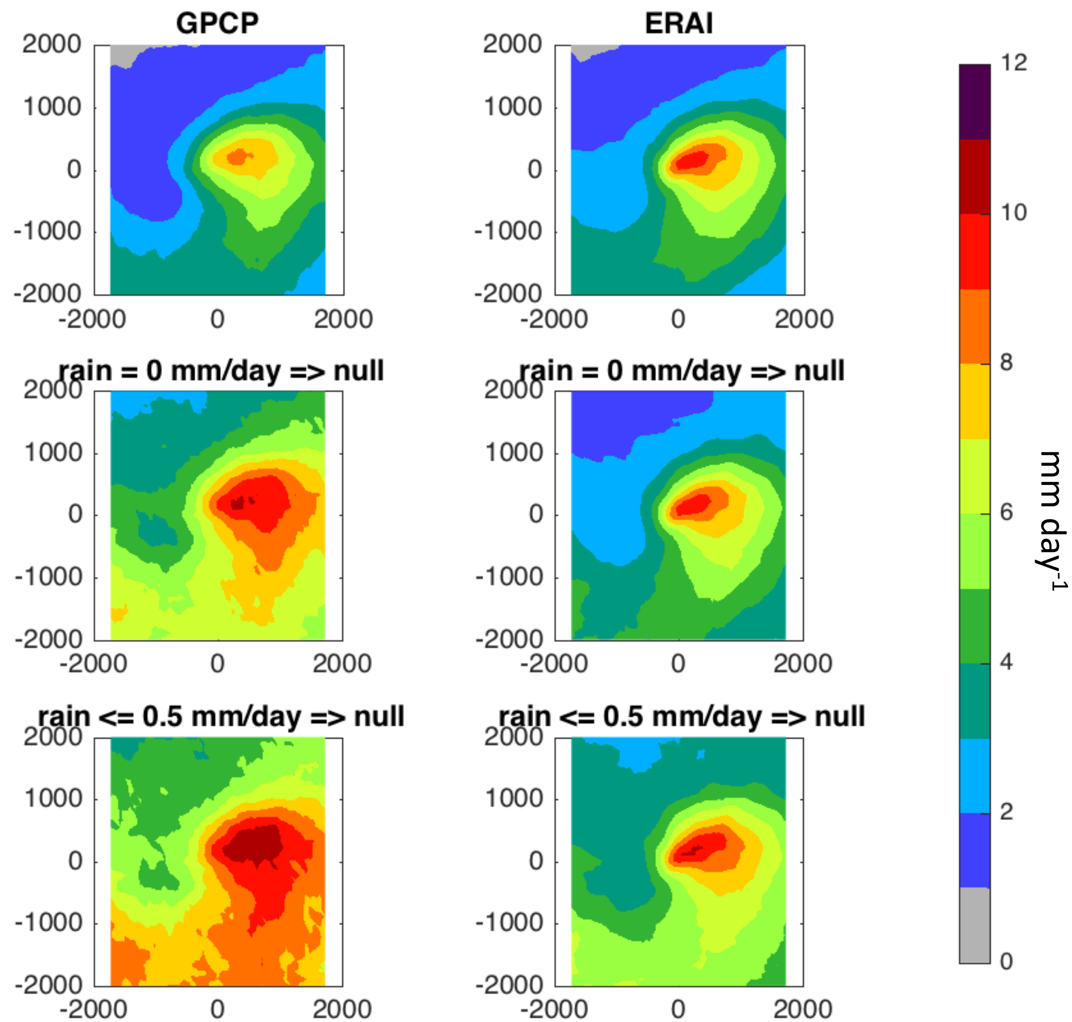
- Possible issue with zero rain (<u>middle row</u>)

- Satellite data have minimum precip. thresholds, below which value is set to zero.

Not the issue here (<u>bottom row</u>).

Work in progress using CloudSAT, GPM

Cyclone- centered Precipitation
N. Atlantic, 2010 – 2014



Temporal resolution is a factor:
GPCP is Daily vs. <u>ERA-Interim 6-hourly</u>

Research Questions

Can GCMs generate spatial distribution and intensity of extratropical cyclone precipitation matching reanalysis and a weather forecast model?

Do modeled cyclone precipitation biases relate to cyclone strength biases?

How does parameterized convection impact cyclone precipitation?

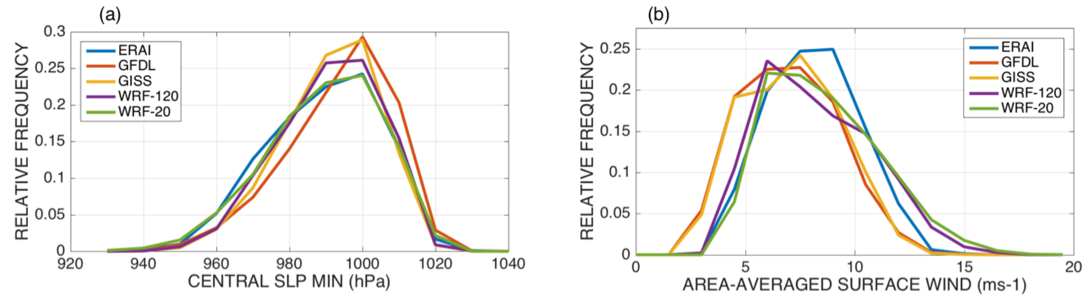
Project 1: CMIP5 models vs. ERAI and WRF

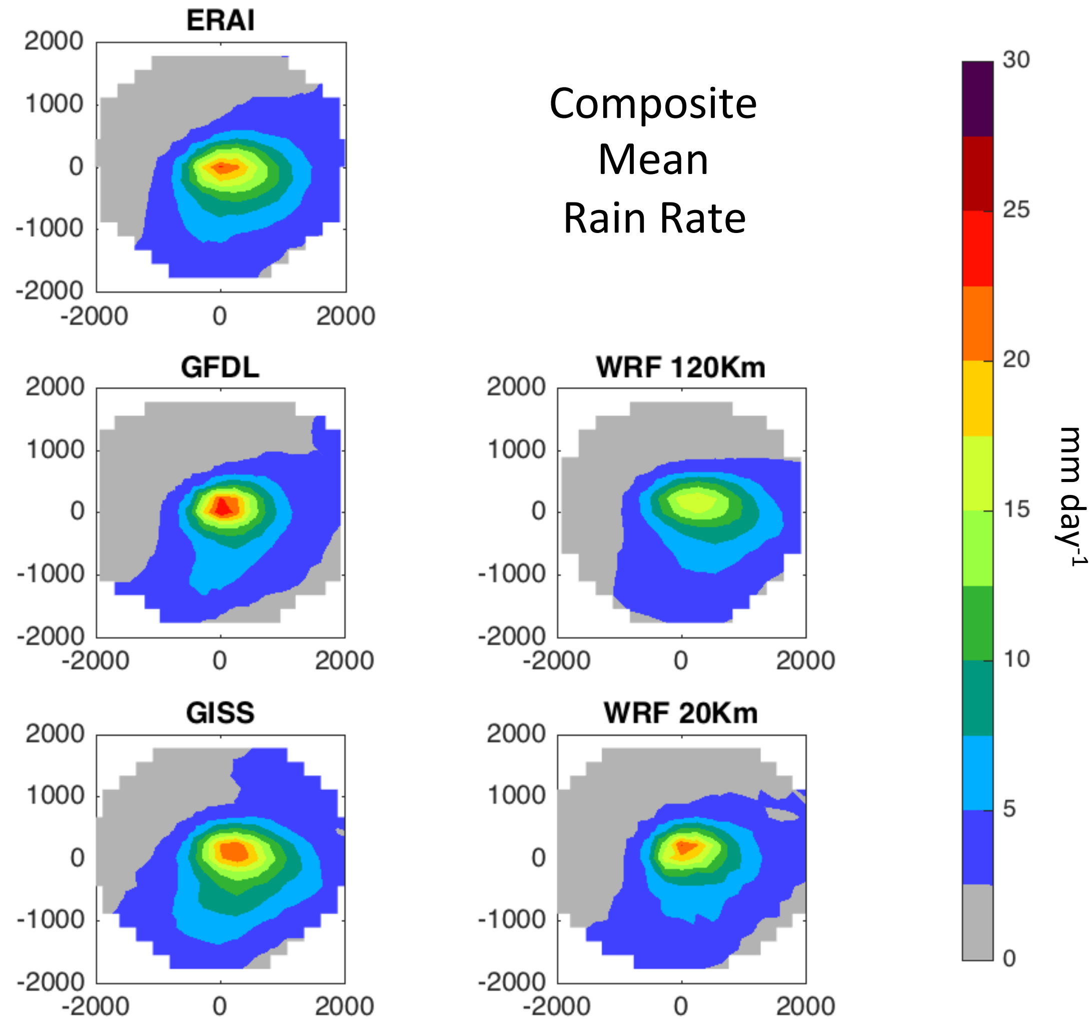
WRF: seasonal runs of weather forecasting model for the N. Atlantic (Willison et al. 2015).

CMIP5 models: 2˚ X 2.5˚
All models regridded to this grid for analysis.

<u>Top panels:</u>
Storm SLP min and surface wind max distributions show GCMs do not generate strongest storms.

<u>Bottom panels:</u>
GFDL more warm front prec. vs ERAI
GISS more cold front prec vs. ERAI
WRF 20km agreement with ERAI





6-hourly, not daily -> big jump in rain rates

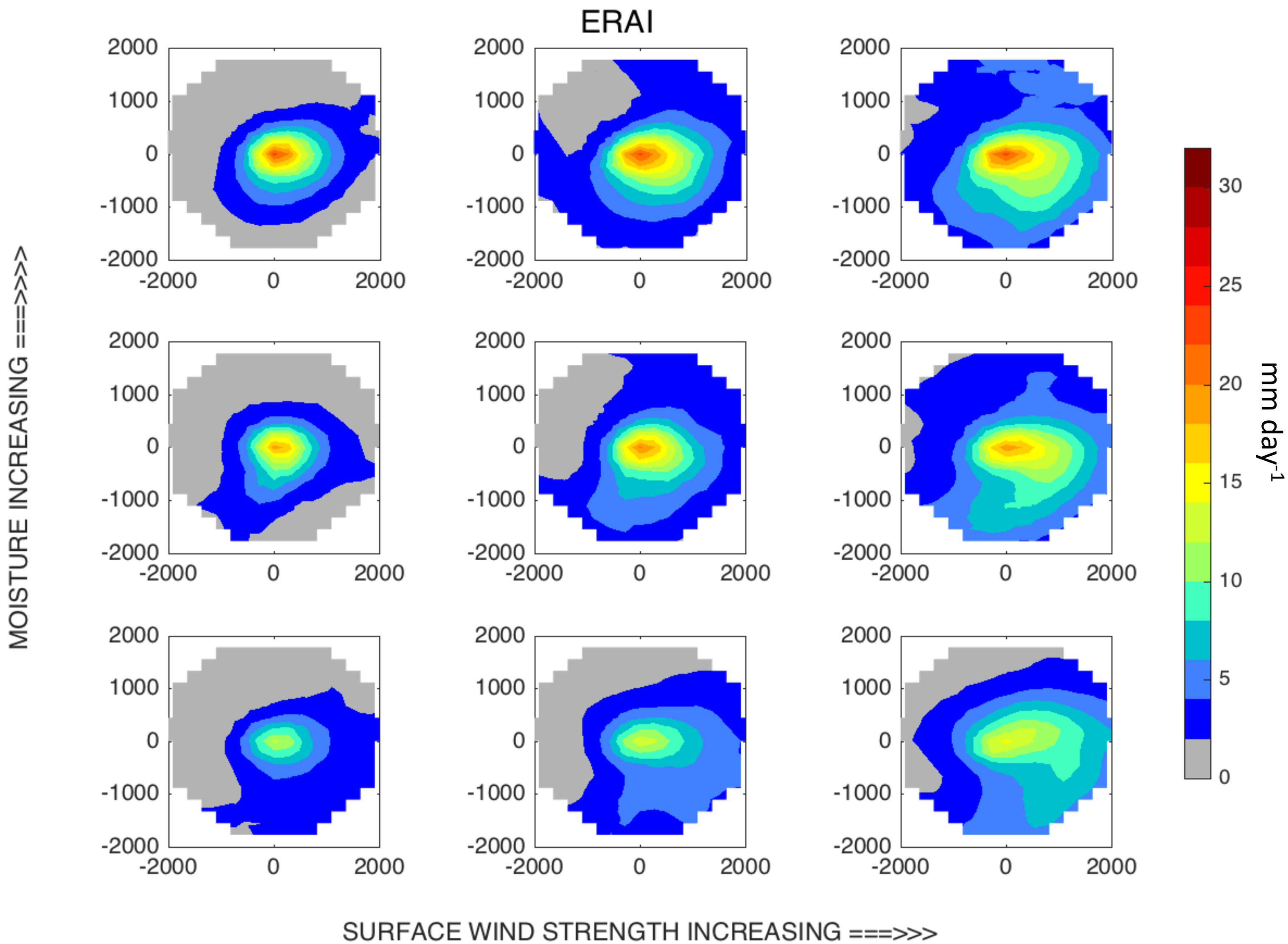
Working towards the processes in the storms:

ETC precipitation versus storm strength and column moisture.

Conditional subsets of cyclone precipitation following Field and Wood, 2007, JCLI

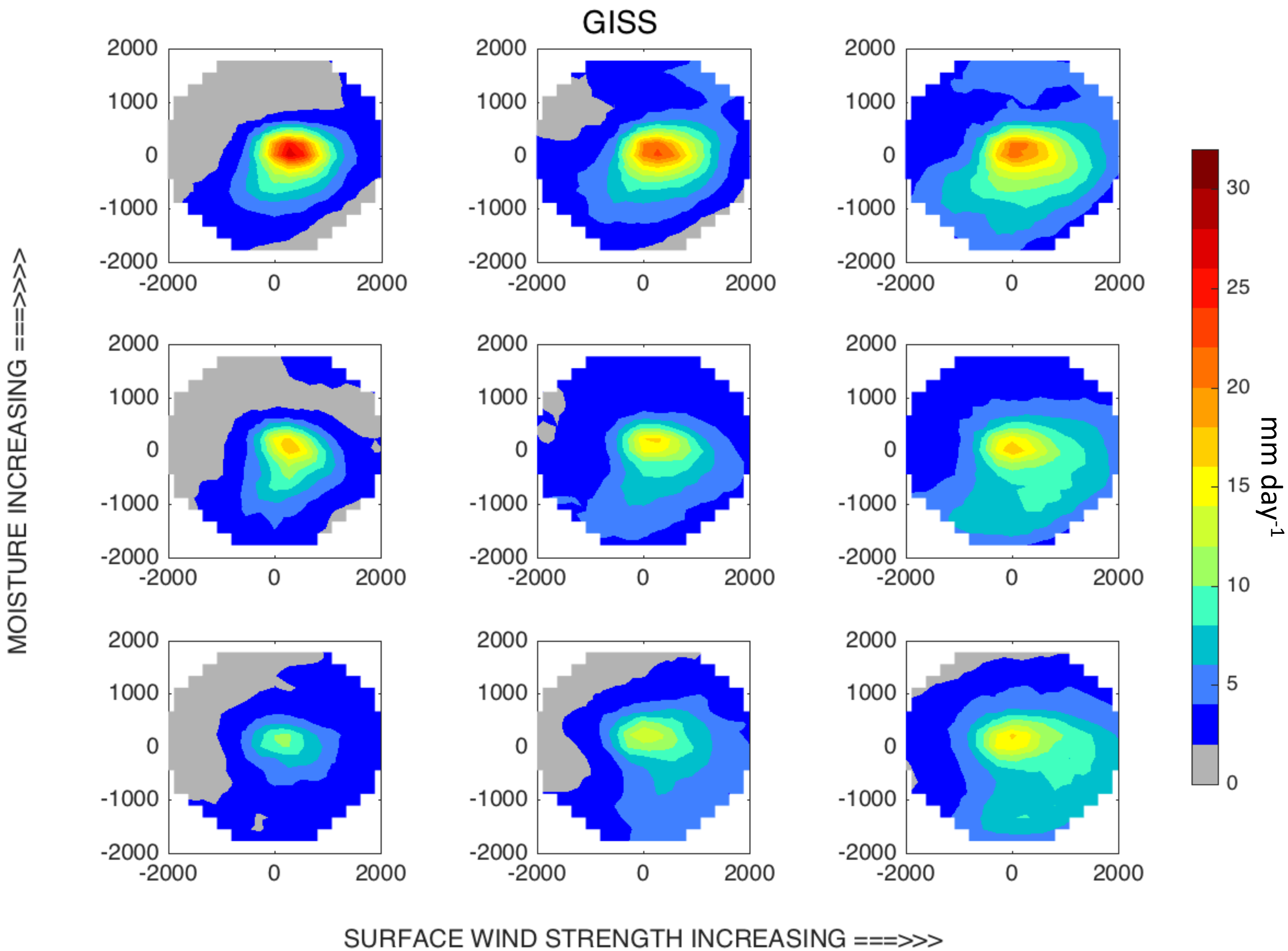
Top row: cyclones with most PWV, for these max prec. intensity does not increase with storm strength. True for N. Atlantic only.

Why: large PWV can occur near Gulf Stream, which is cyclone genesis region, when storms are not strong yet



Result: GCM cyclone precipitation varies with storm strength and moisture in same manner as reanalysis.

- For low moisture, precip region and intensity increases with strength
- For high moisture, precip region increases, intensity does not.

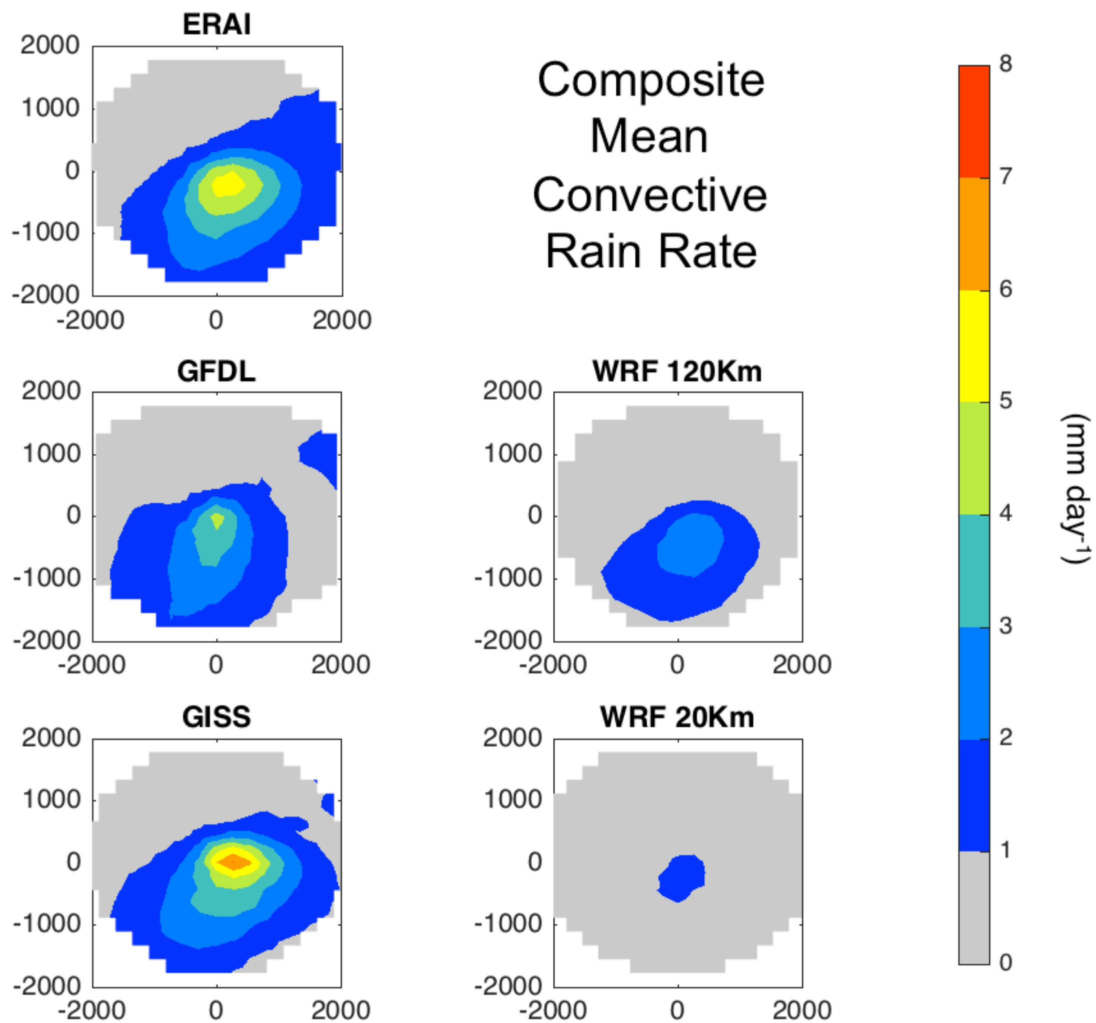


Similar results for GFDL and WRF.

“Convective Precipitation”:
model diagnostic identifying precipitation generated by convection scheme.

- lower limit on model convective precipitation, because convection can also be resolved.
- Diagnostic also depends on parameterization implementation/design philosophy
- That being said, it does correspond with regions of vertical instability in the cyclones.

Model to model differences are as large as differences in precipitation (from 3 slides ago)



Color scale is 1/4 of that used for total precip.

Field and Wood, 2007, Warm Conveyor Belt Model:

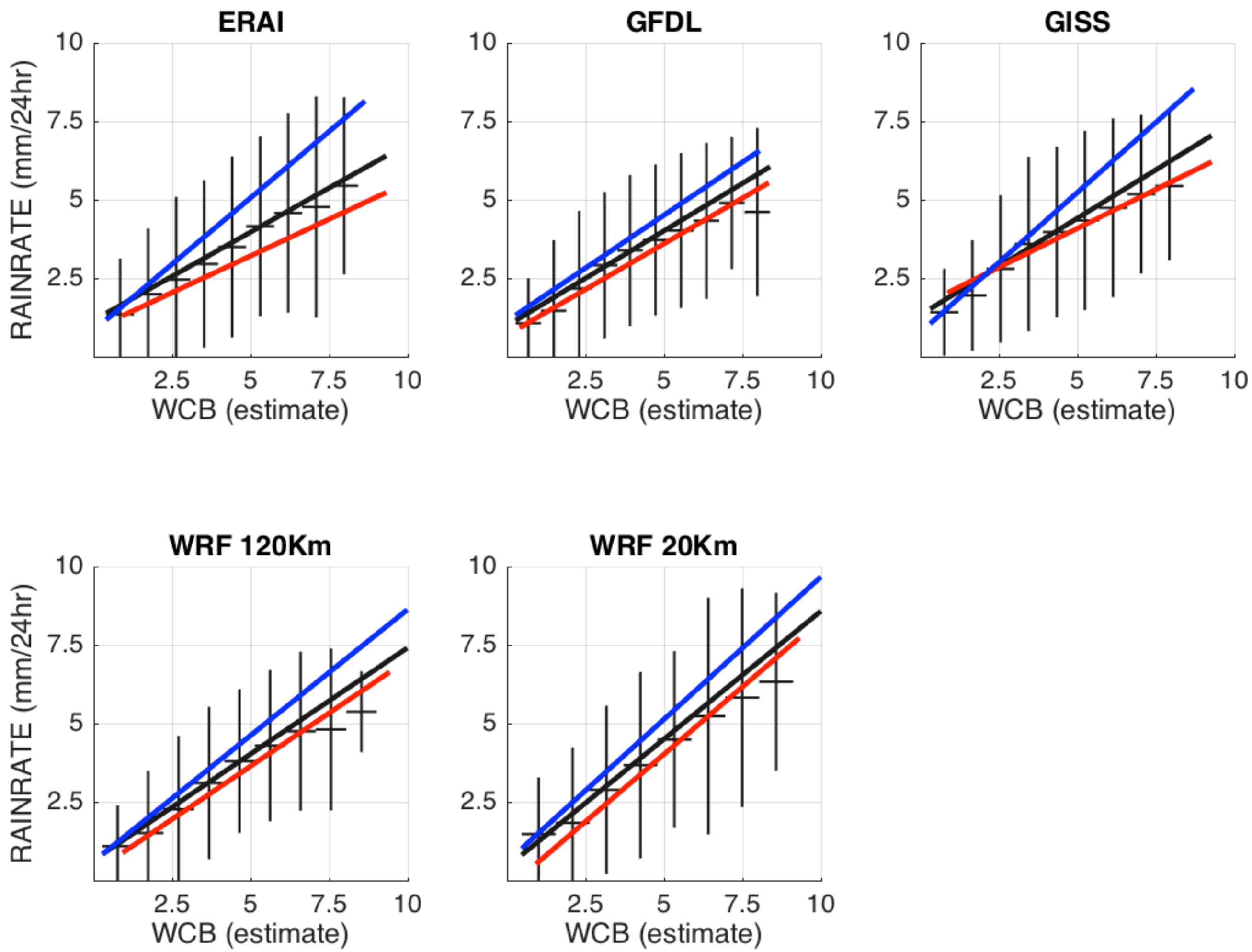
$$R_{WCB} = k * \langle WSPD_{SURF} \rangle \langle PWV \rangle$$

<*> indicates cyclone-centered area average

Sort cyclones into 3 sets based on percentage of convective precipitation (convfrac)

Black: full dataset
Blue: lower 1/3 convfrac
Red: higher 1/3 convfrac

When convection scheme is more active, WCB overestimates actual model precipitation



- *The work on CMIP5 models has been submitted to JCLIM*

Project 2: "CMIP6 Prototype" Models vs. Reanalysis

GFDL and NCAR AMIP model experiments, as part of NOAA Model Diagnostic Task Force (MDTF)

Two versions of the GFDL model:

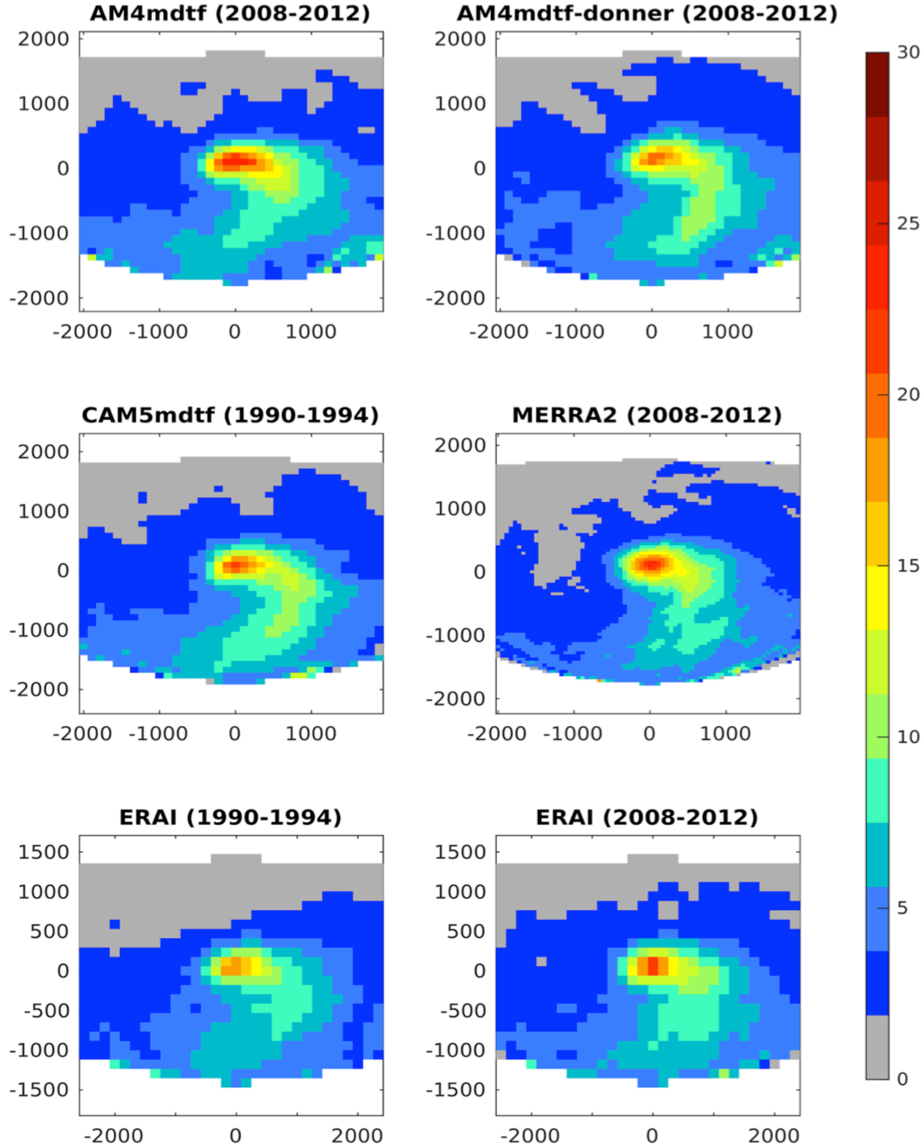
- AM4 (2-plume convection scheme).
- AM4 with Donner convection scheme, and different tuning for radiative balance.
- Cubed-sphere with resolution near 1˚x1˚

Precipitation composites are for cyclones at 1-day prior max wind speeds. DJF, North Pacific

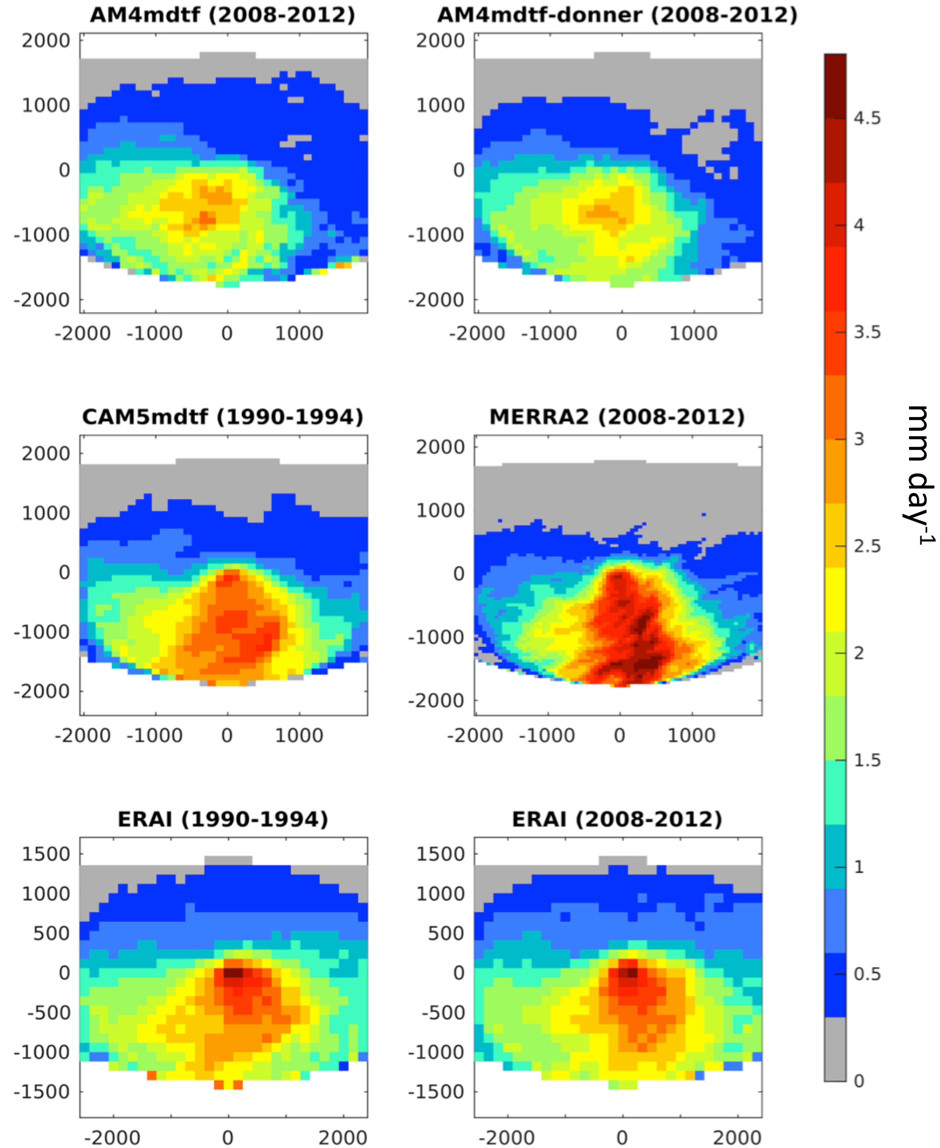
Arrangement of the models for the figures

GFDL-MDTF AM4 (2008 – 2012)	GFDL-MDTF AM4-Donner (2008 – 2012)
NCAR-MDTF CAM5 (1990 – 1994)	MERRA2 (2008 – 2012)
ERA-Interim (1990 – 1994)	ERA-Interim (2008 – 2012)

Precipitation Composite
(mm day^{-1})



Convective Precipitation Composite,
(mm day^{-1})

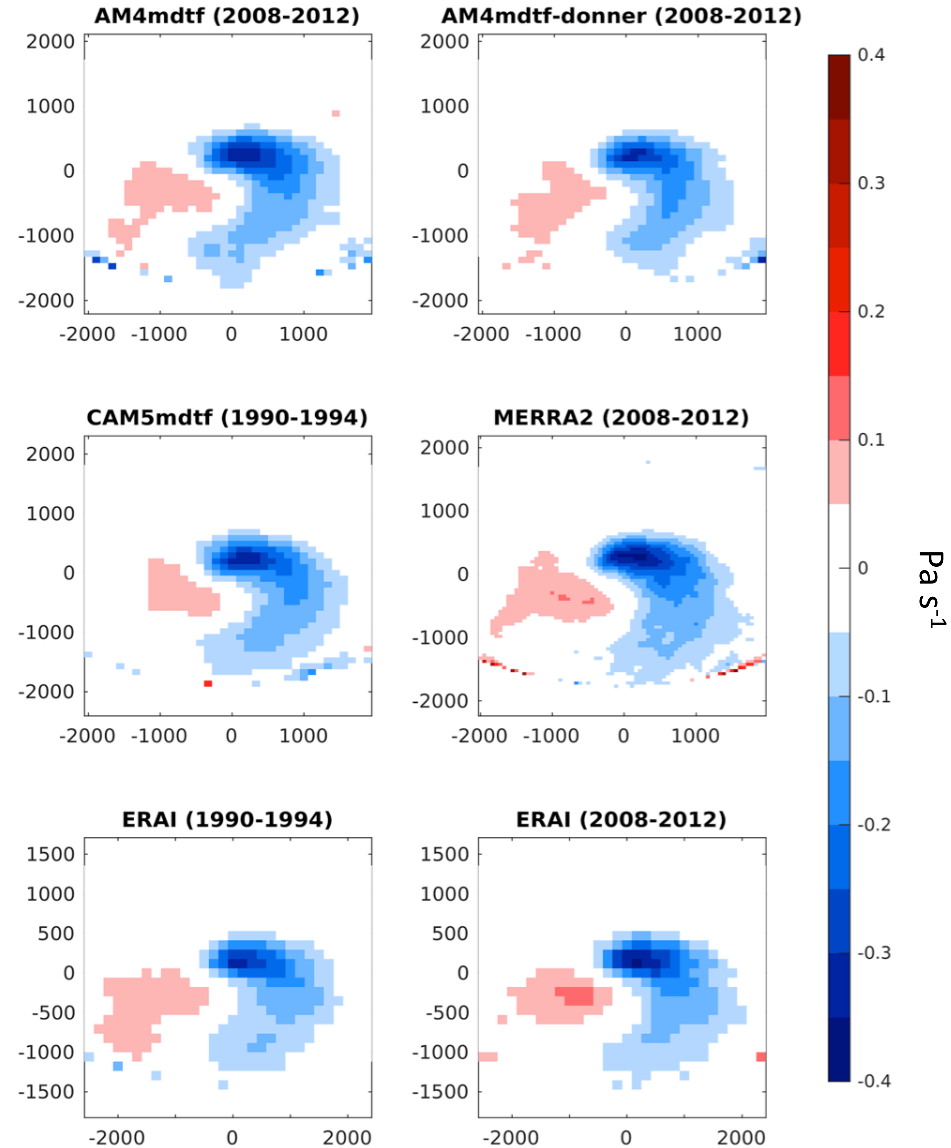


- Models match reanalysis precip relatively well; excess prec ahead of cold front.
- Reanalyses have as much or more parameterized precip than the models

Vertical Velocity at 500 hPa

- Differences in amount of convective precipitation are not apparent in the vertical velocity field
- Results are an improvement from lower resolution CMIP5 models.
- Matching vertical velocity with reanalysis has been shown for the HiGEM model: Hawcroft et al. 2017, Cli Dyn.

ω at 500 hPa Composite, DJF, North Pacific (Pa s^{-1})

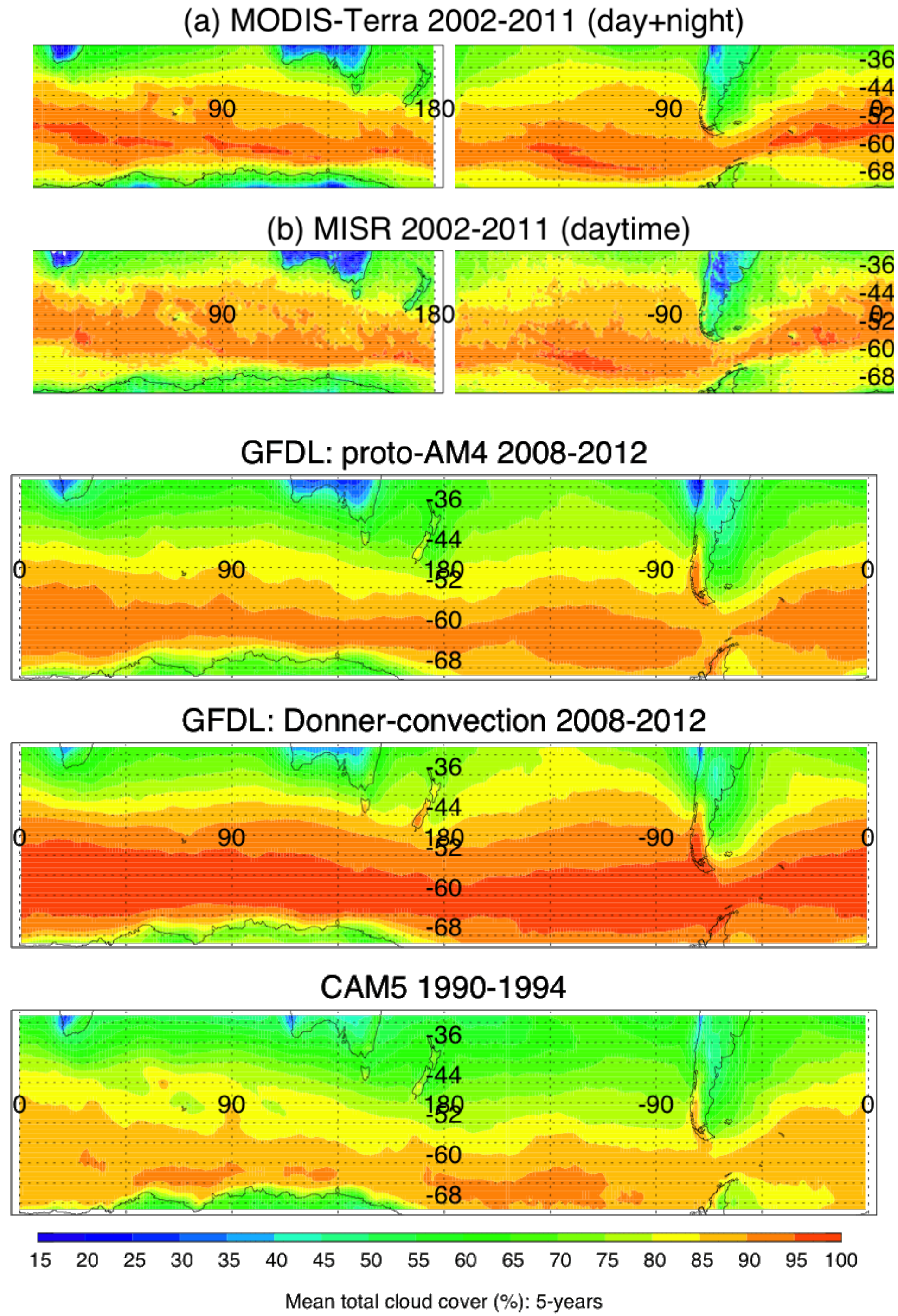


Model evaluation: total cloud cover (TCC) in SH oceans

Before looking at cyclones, we examine full cloud field

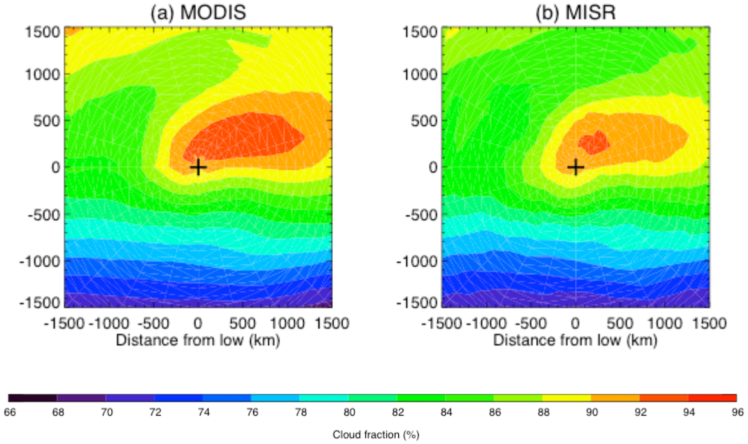
Top 2 panels:
Satellite observations: differences around 5% estimate the uncertainty in the obs.
Naud et al. 2013, JGR

- GFDL-AM4: TCC close to observations
- Donner-convection: TCC slightly overestimated
- CAM5: Too few clouds



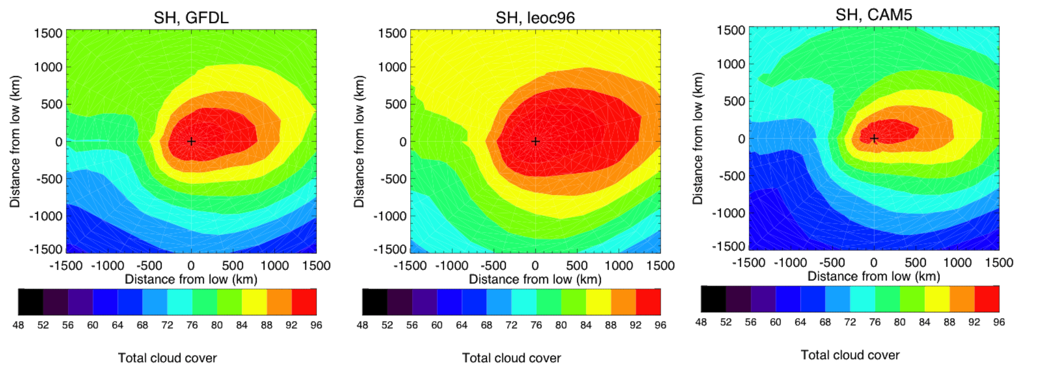
2D total cloud cover
SH extratropical cyclones in JJA

At right: observations: MODIS and MISR
Below: the models



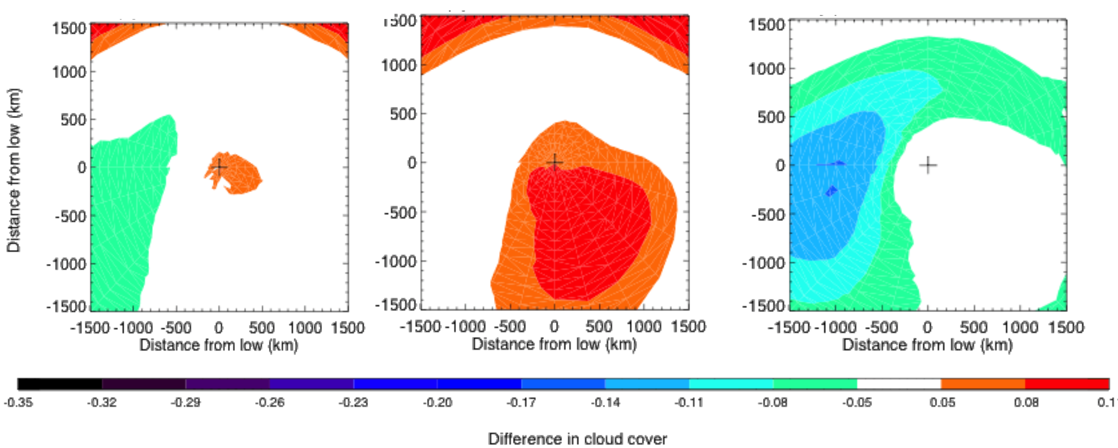
Comparison between MODIS and MISR: differences at most 4-6%
Naud et al., JGR 2013

GFDL-AM4 | AM4-Donner | CAM5



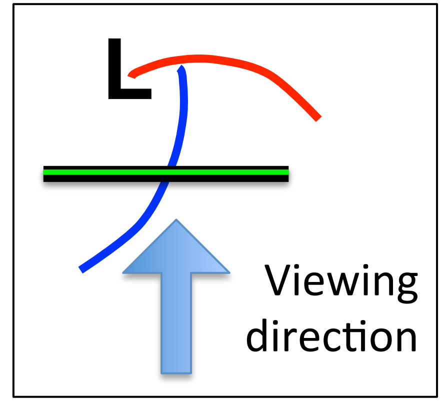
Reanalysis and Models, minus MODIS

GFDL-AM4 | AM4-Donner | CAM5

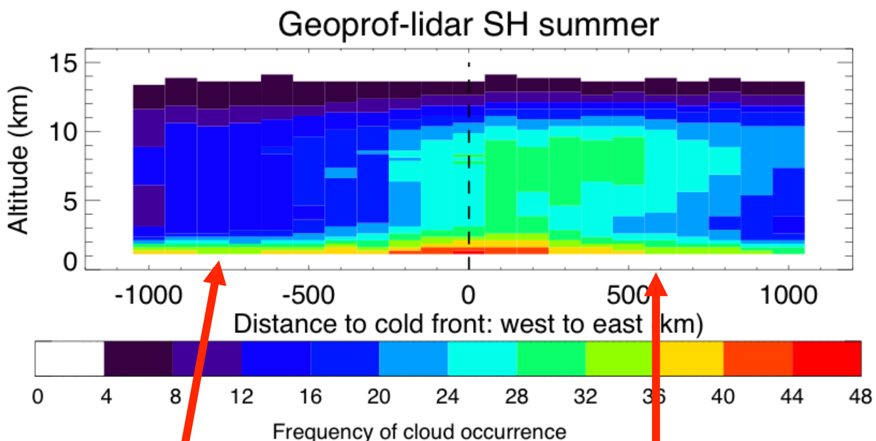


- Warm sector: AM4 and CAM5 close (diff +2-5%) to obs. , Donner-conv too much cloud
- Cold sector: AM4 < MODIS Donner-conv ≃ MODIS, negative bias in CAM5

Vertical cloud distribution across cold fronts



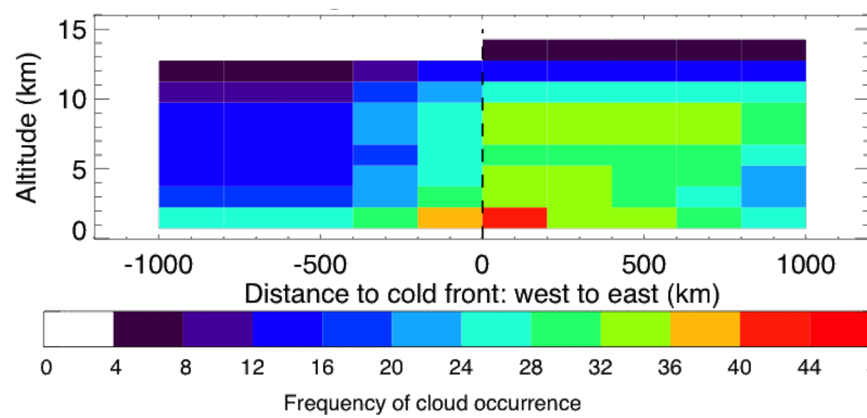
CloudSAT/CALIPSO



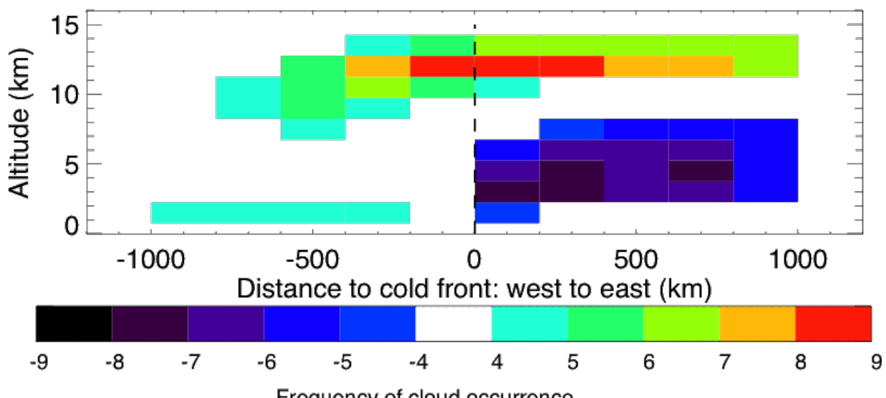
Cold sector = low-level clouds

Warm sector= clouds at all level

AM4: less low clouds in cold sector, more clouds in warm sector



Donner-Conv minus AM4



Donner-convection: cold sector low clouds close to observations, more high clouds on both sides of front

Donner-convection top heavy vs. AM4

SUMMARY AND CONCLUSIONS

- GCMs, weather models, and reanalysis generate similar cyclone-composite precipitation
- However, the amount of precipitation generated via parameterized convection differs model to model.

<u>Modeled precipitation amount in the cyclones seemingly independent of the amount of precipitation generated by the convection schemes</u>

- GCMs and reanalysis show similar cyclone precipitation response to variability in storm strength and atmospheric moisture.
- Fraction of Convective precipitation impacts the fit of the data to the warm conveyor belt (WCB) model.

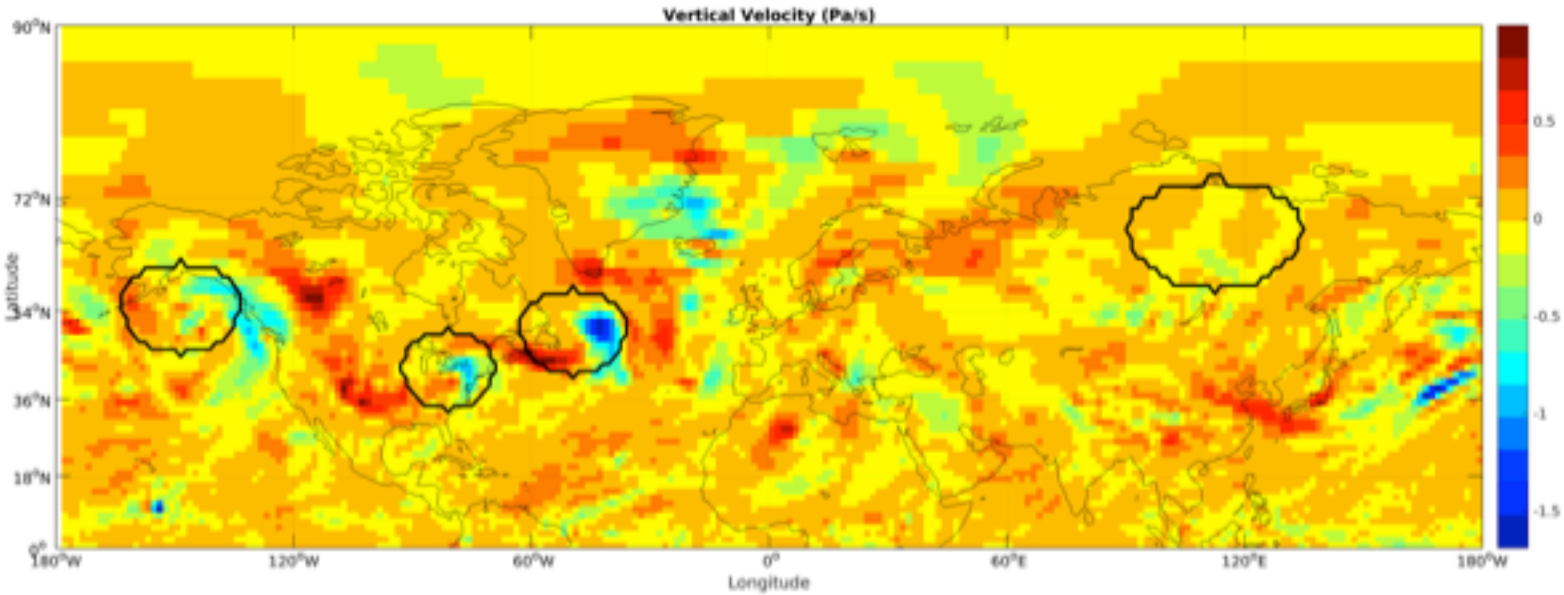
<u>More convection means less precipitation than the WCB model predicts.</u>

- CMIP6 models show improvement in cyclone clouds

<u>Extratropical cyclone cloud cover is sensitive to the convection scheme</u>

For diagnostic sake: can we remove the tracking step?

Is it possible to identify cyclone circulation regimes based on conditional subsetting?



Test #1: compare cyclone and non-cyclone circulation characteristics

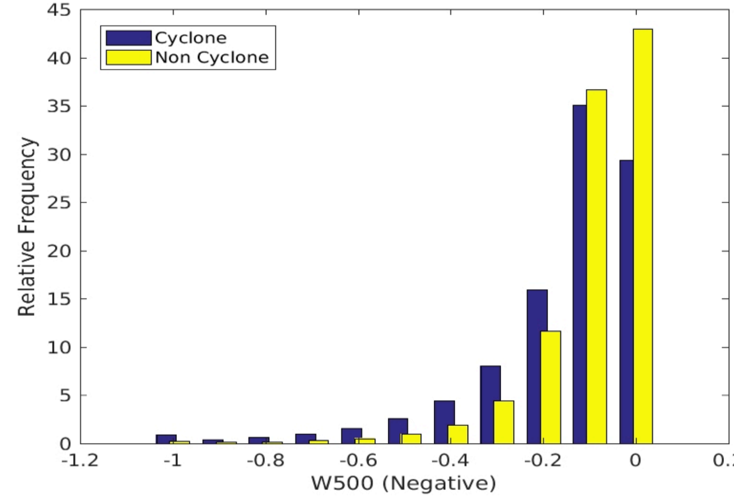
“cyclone” regions within 2000 km of tracked cyclone centers
“non-cyclone” all other regions in the midlatitudes.

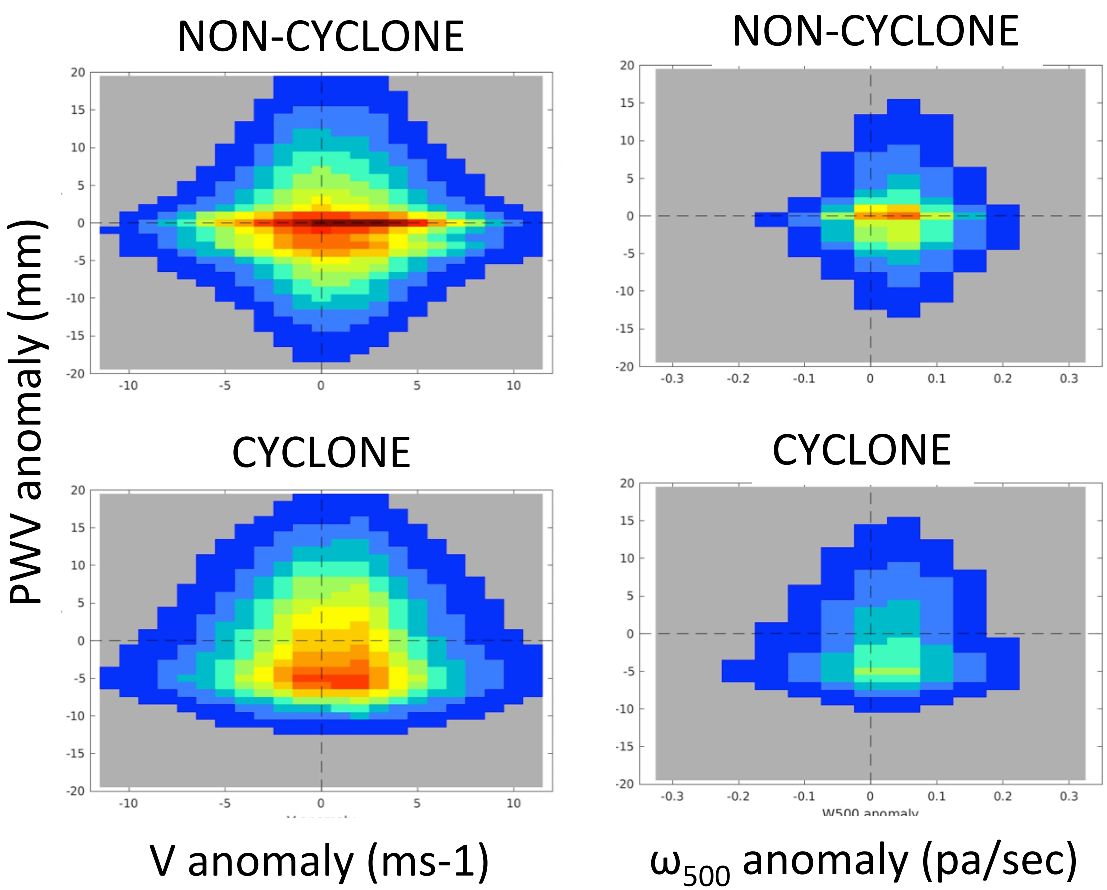
Top right: distribution of $\omega_{500}<0$ for cyclone (blue) and non-cyclone (yellow)

Bottom: 2-d histograms

Right: meridional wind vs. PWV

Left: ω_{500} vs. PWV





Numbers irrelevant at the stage
Red mean more data points.

Cyclone and non-cyclone distributions differ… but the overlap is strong, making it difficult to pin-point storms with this method.

Alternate: identify regions of strong ascent, mask mountain region.

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Extratropical cyclone cloud cover is sensitive to the convection scheme

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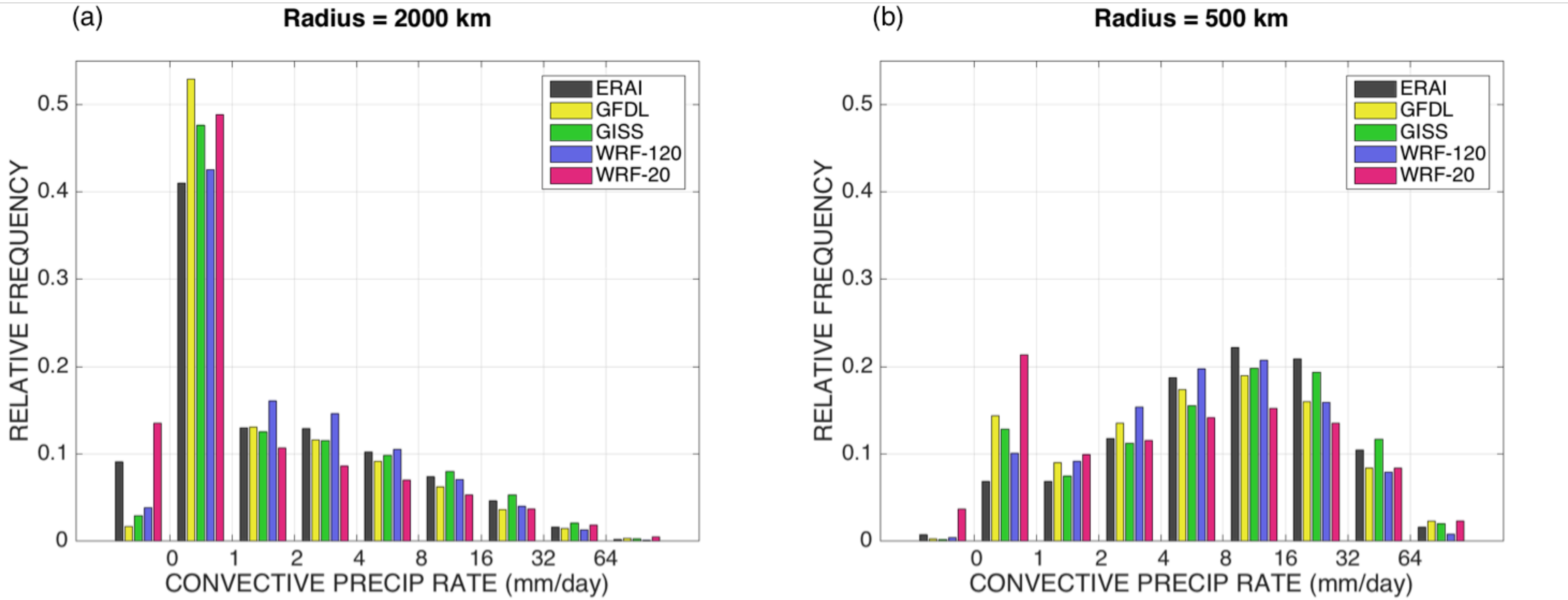
EXTRA SLIDES

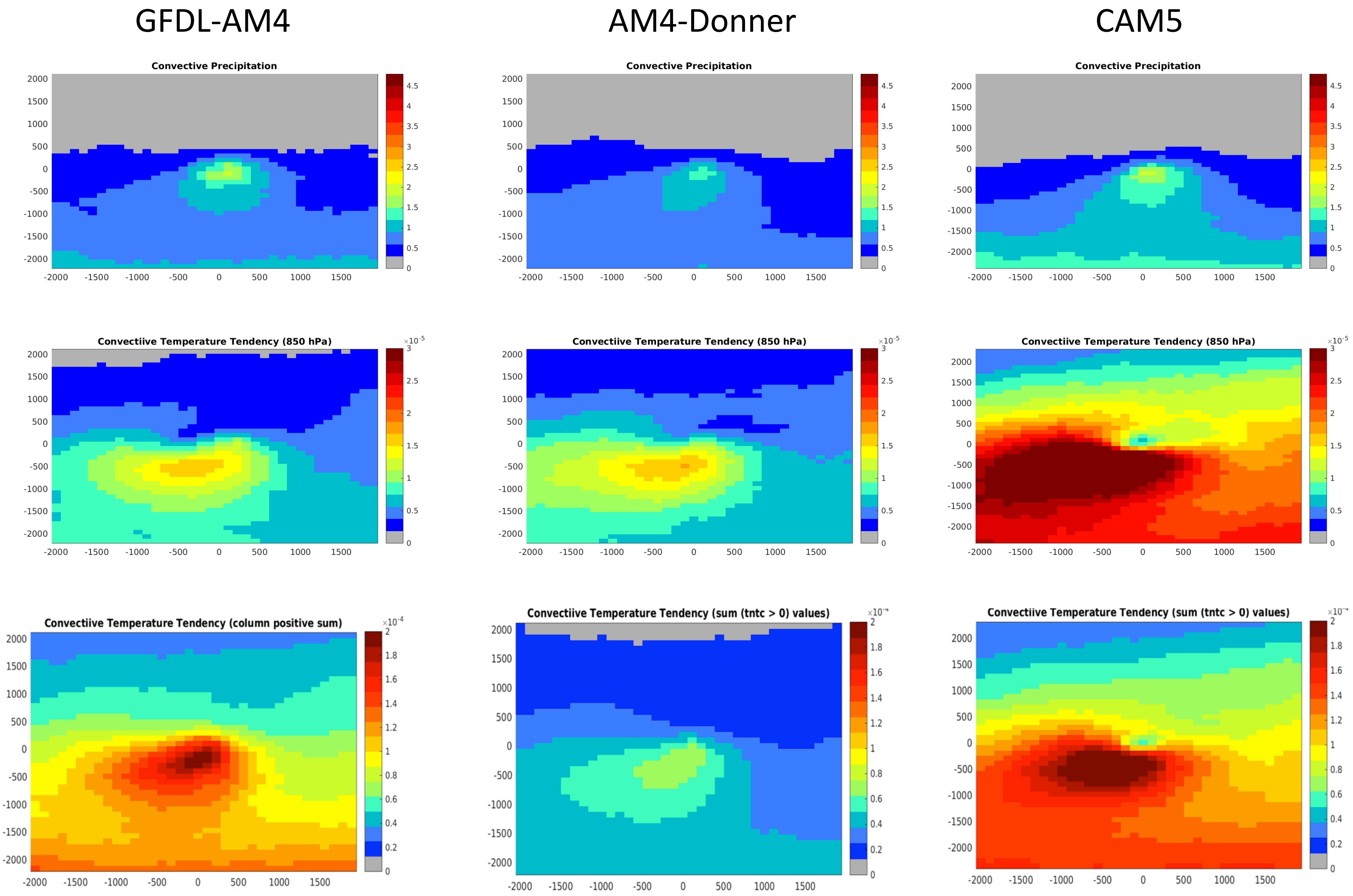
Project 1: CMIP5 models vs. ERAI and WRF

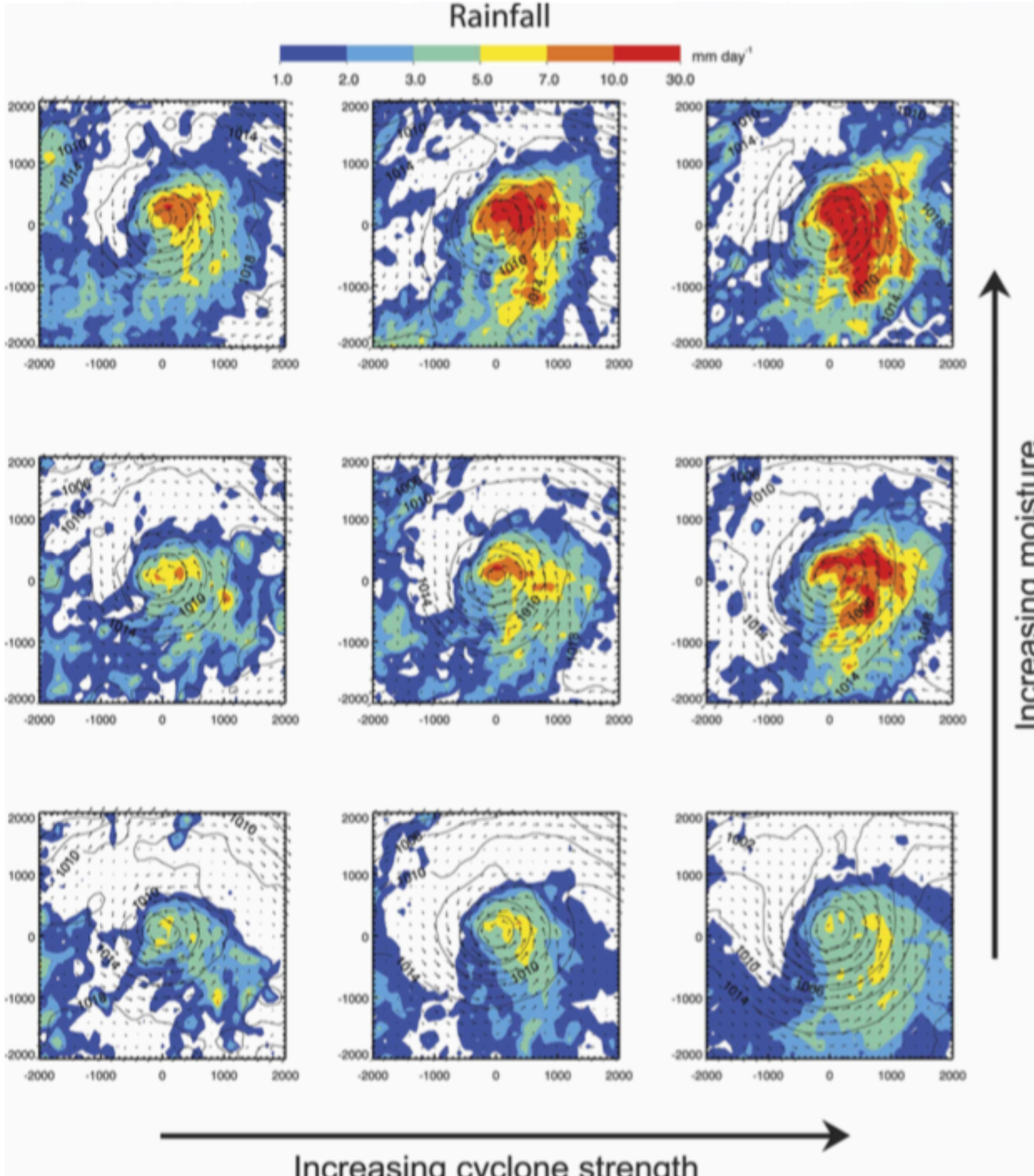
Distribution of prec rates for points within 2000 or 500 km radius of the cyclone center



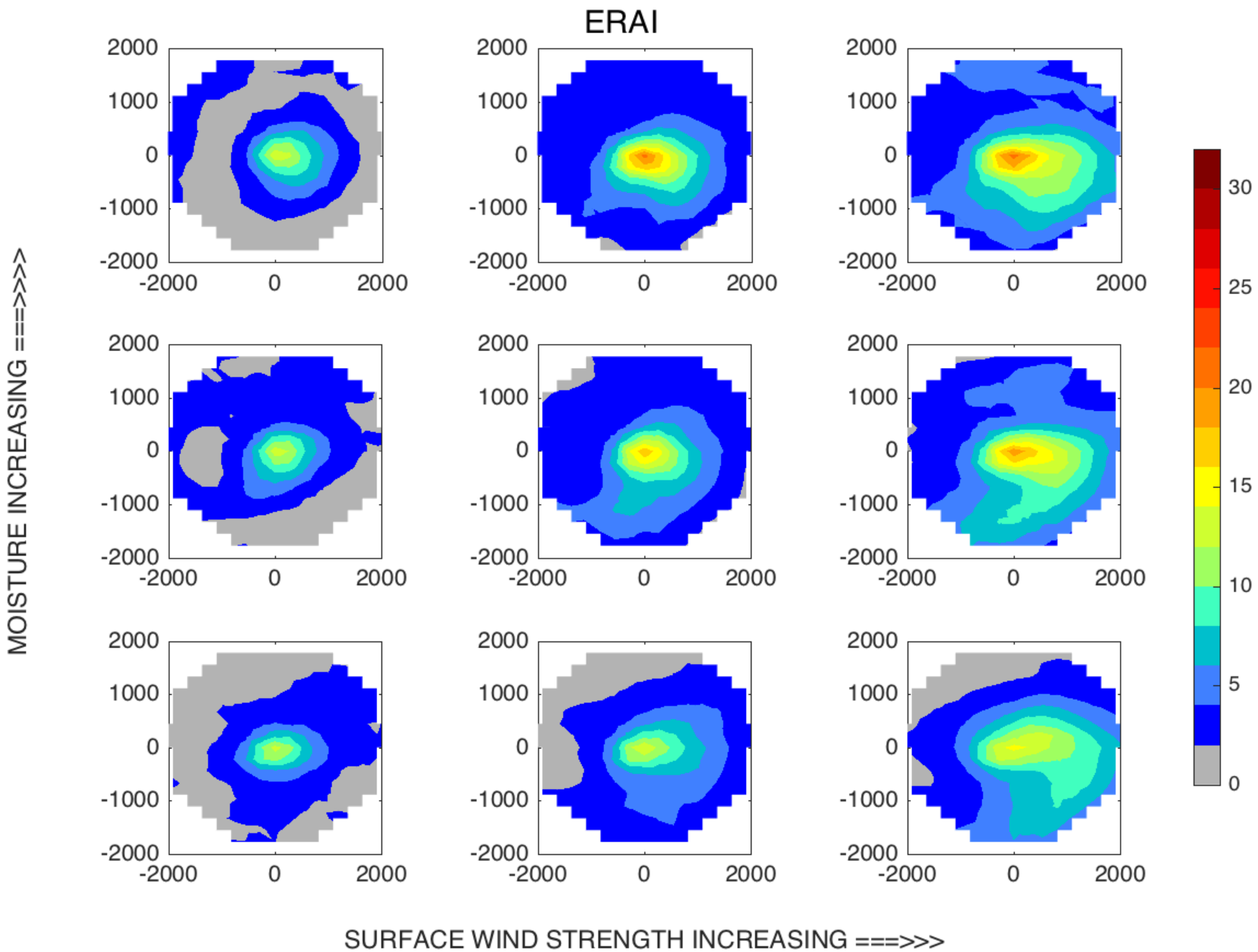
- WRF 20 km generates more precip at the tails: more zero/ near zero and more of the largest rates.

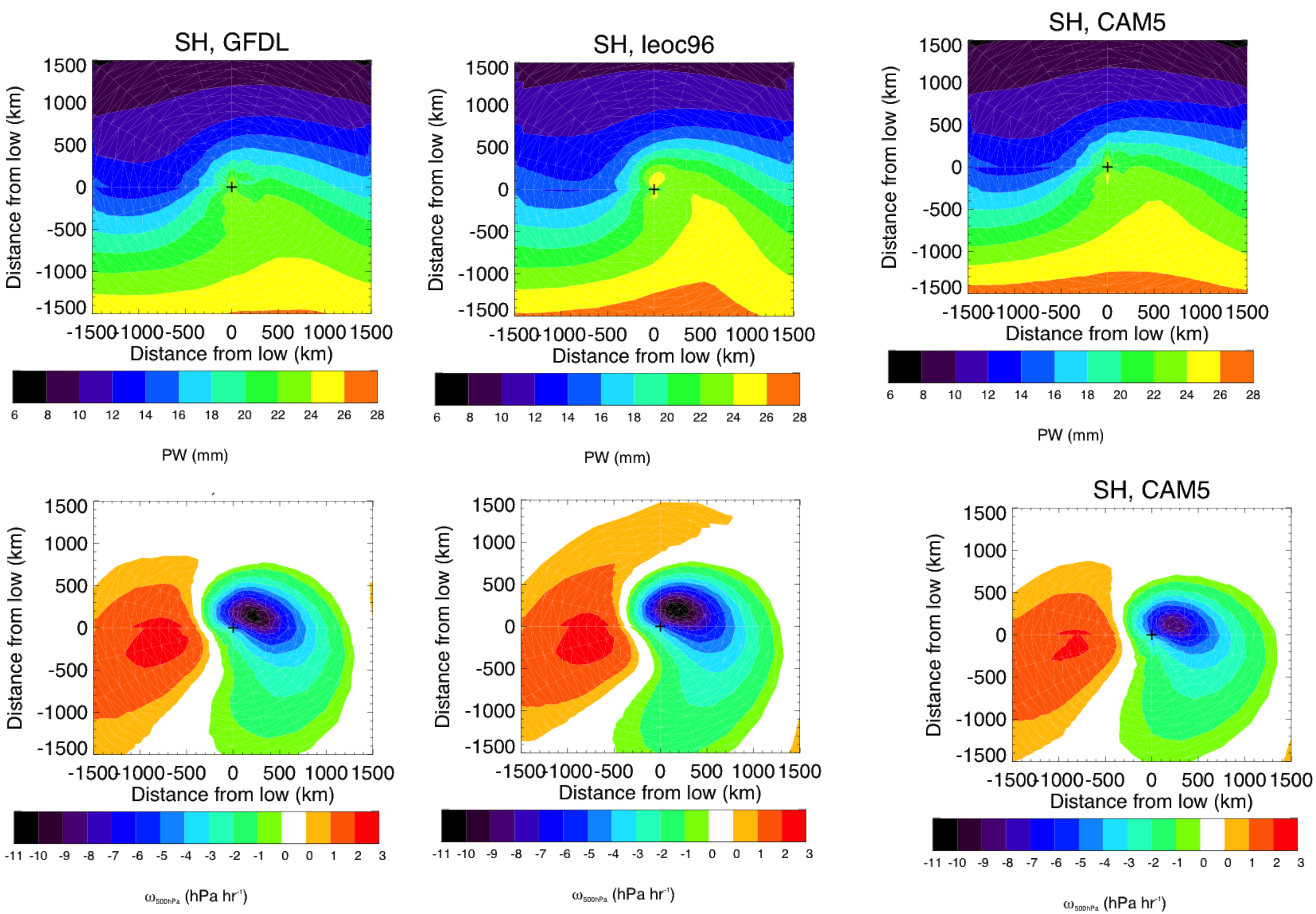
- Large fraction at 0 – 1 mm day-1 in 20km WRF is not caused by regridding.


GFDL-AM4
AM4-Donner
CAM5
Convective Precipitation
Convective Precipitation
Convective Precipitation
Convectiive Temperature Tendency (850 hPa)
Convectiive Temperature Tendency (850 hPa)
Convectiive Temperature Tendency (850 hPa)
×10^-5
Convectiive Temperature Tendency (column positive sum)
×10^-4
Convectiive Temperature Tendency (sum (tntc > 0) values)
Convectiive Temperature Tendency (sum (tntc > 0) values)
-2000 -1500 -1000 -500 0 500 1000 1500
2000 1500 1000 500 0 -500 -1000 -1500 -2000
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
0 0.5 1 1.5 2 2.5 3
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2


Rainfall
mm day⁻¹
1.0
2.0
3.0
5.0
7.0
10.0
30.0
Increasing moisture
Increasing cyclone strength

REPEAT THE ANALYSIS EXCLUDING STORMS OVER THE GULF STREAM





SH, GFDL
SH, leoc96
SH, CAM5
Distance from low (km)
PW (mm)
SH, CAM5
ω500hPa (hPa hr-1)

Proto-AM4 vs. Donner-convection: stratiform vs. convective cloud cover transects

Convective cloud cover in Donner-convection larger than for proto-AM4 at mid/high level + large-scale cloud cover larger at low-level in cold sector