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Environmental Controls on Marine Stratocumulus Cloud Fraction

CASEY D. BURLEYSON[12] and SANDRA E. YUTER[2]

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With funding by: DOE grants ASR DE-SC0006994 and ASR DE-SC0006701, NOAA grant GC08-252b, NASA grant NNX11AE98G, and NASA Earth and Space Science Fellowship NNX10AP43H

Working Definition of Cloud Fraction

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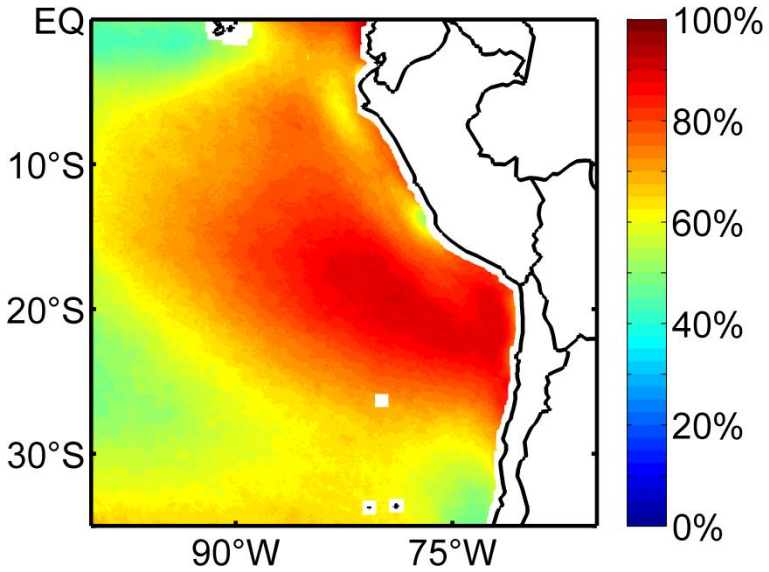
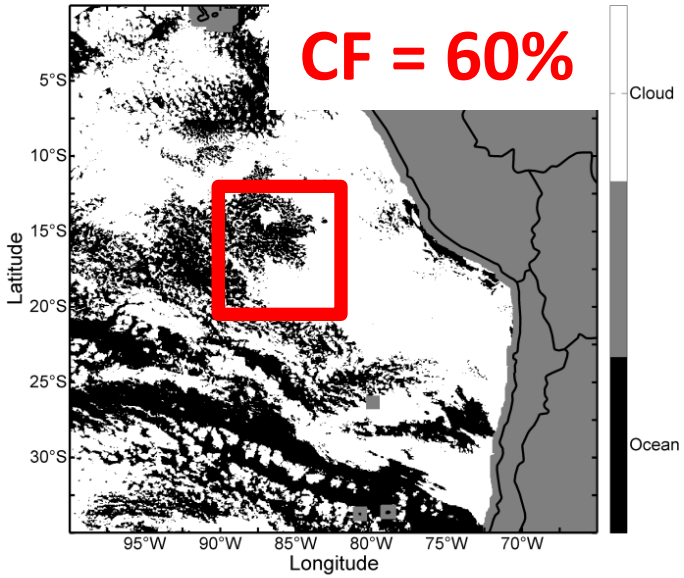
Nighttime Mean MODIS Cloud Fraction



Single Scene Cloud Map



At a given point over a range of time: CF = f(t)

Over an area at a given time: CF = f(x,y)

Annual Mean Stratocumulus Cloud Fraction

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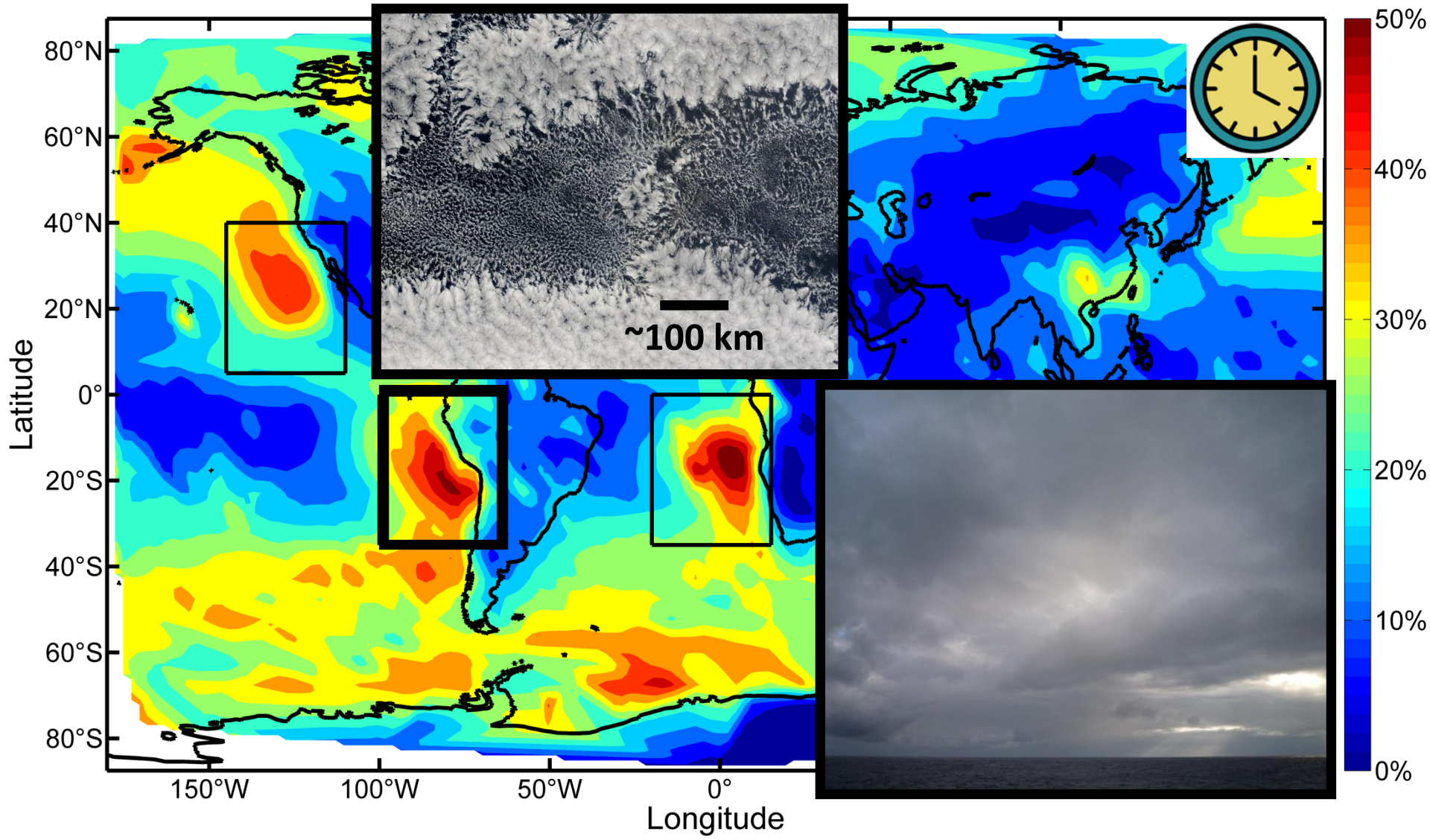

Data from the Cloud Atlas Database (Hahn and Warren 2007)

Cloud Fraction Variability
Mesoscale, Longitudinal, Synoptic

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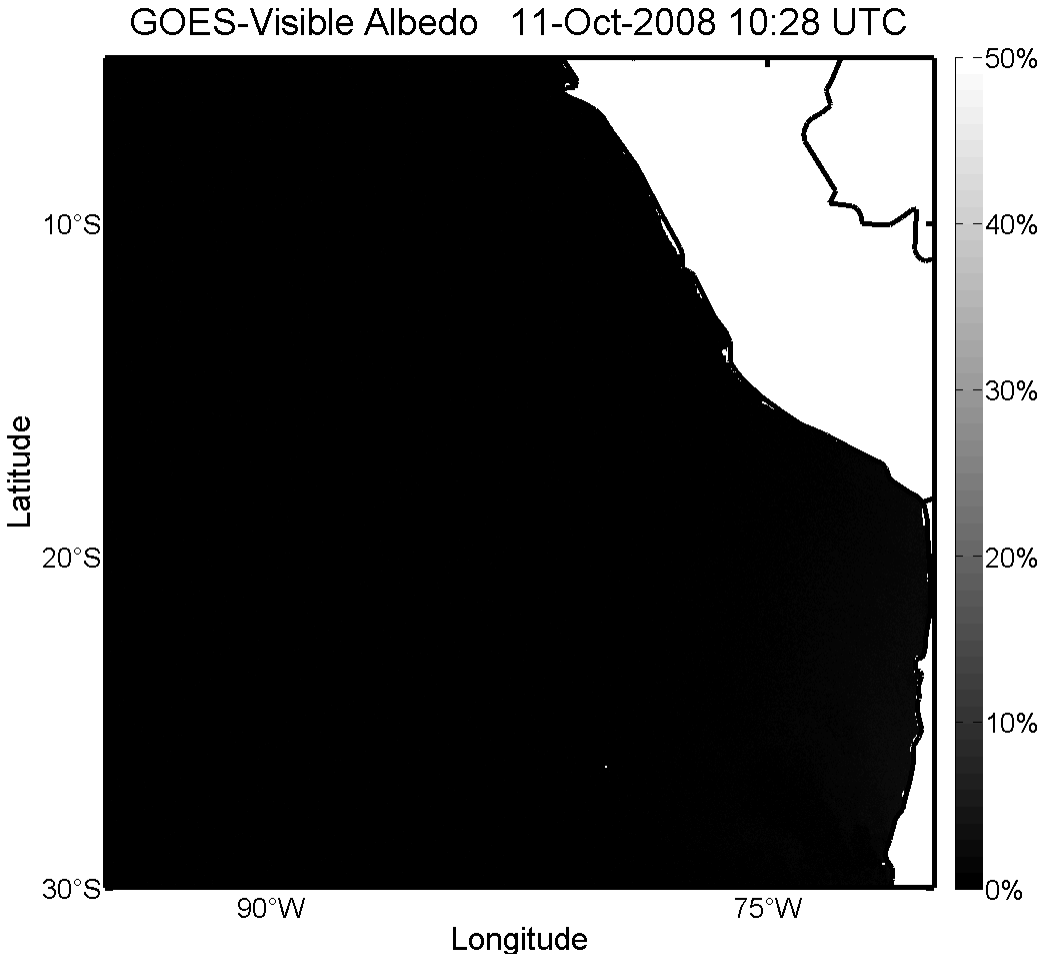

Cloud Fraction Variability
Diurnal

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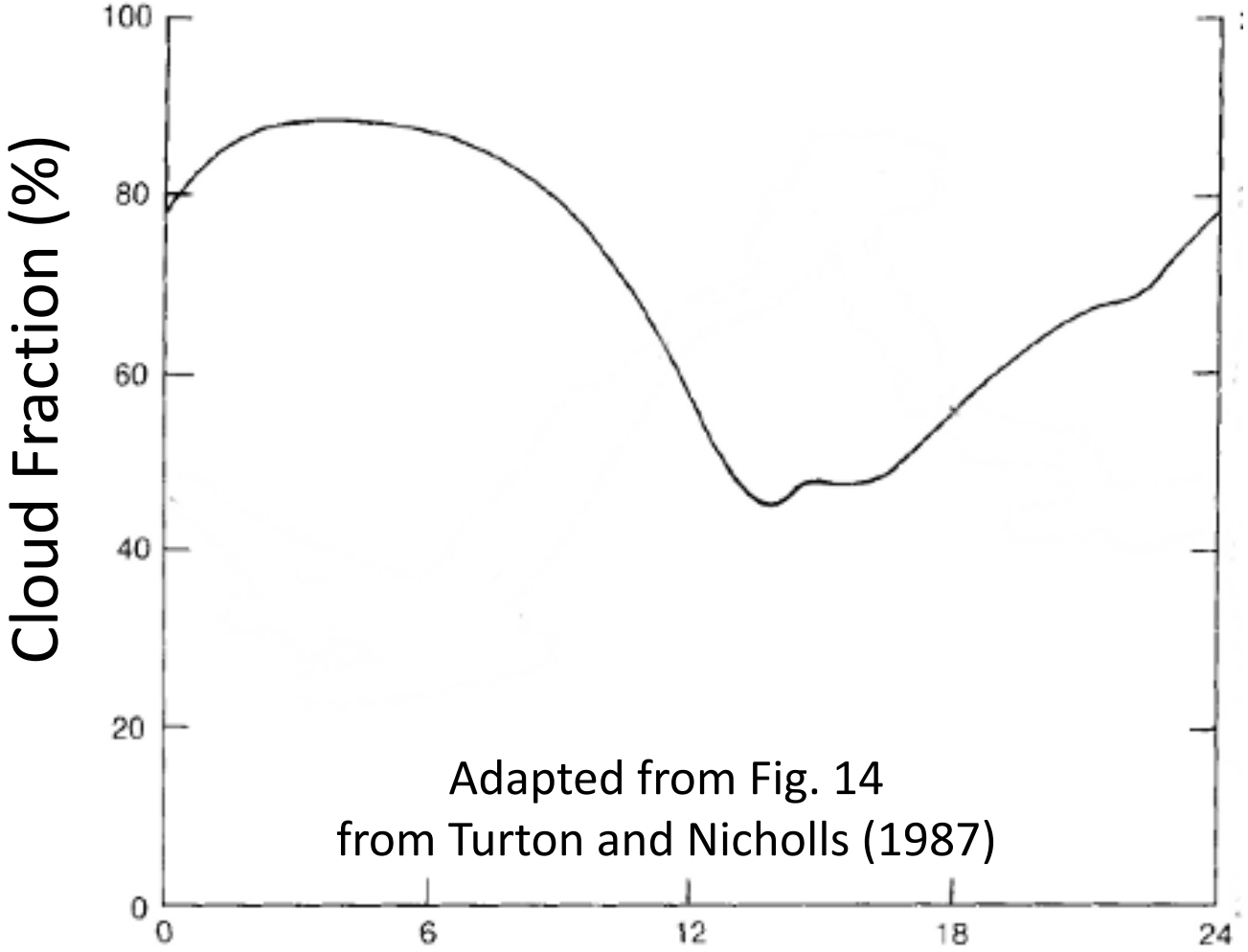
Diurnal Cycle of Cloud Fraction in the SE Pacific



Adapted from Fig. 14
from Turton and Nicholls (1987)

Cloud Fraction Variability
Seasonal

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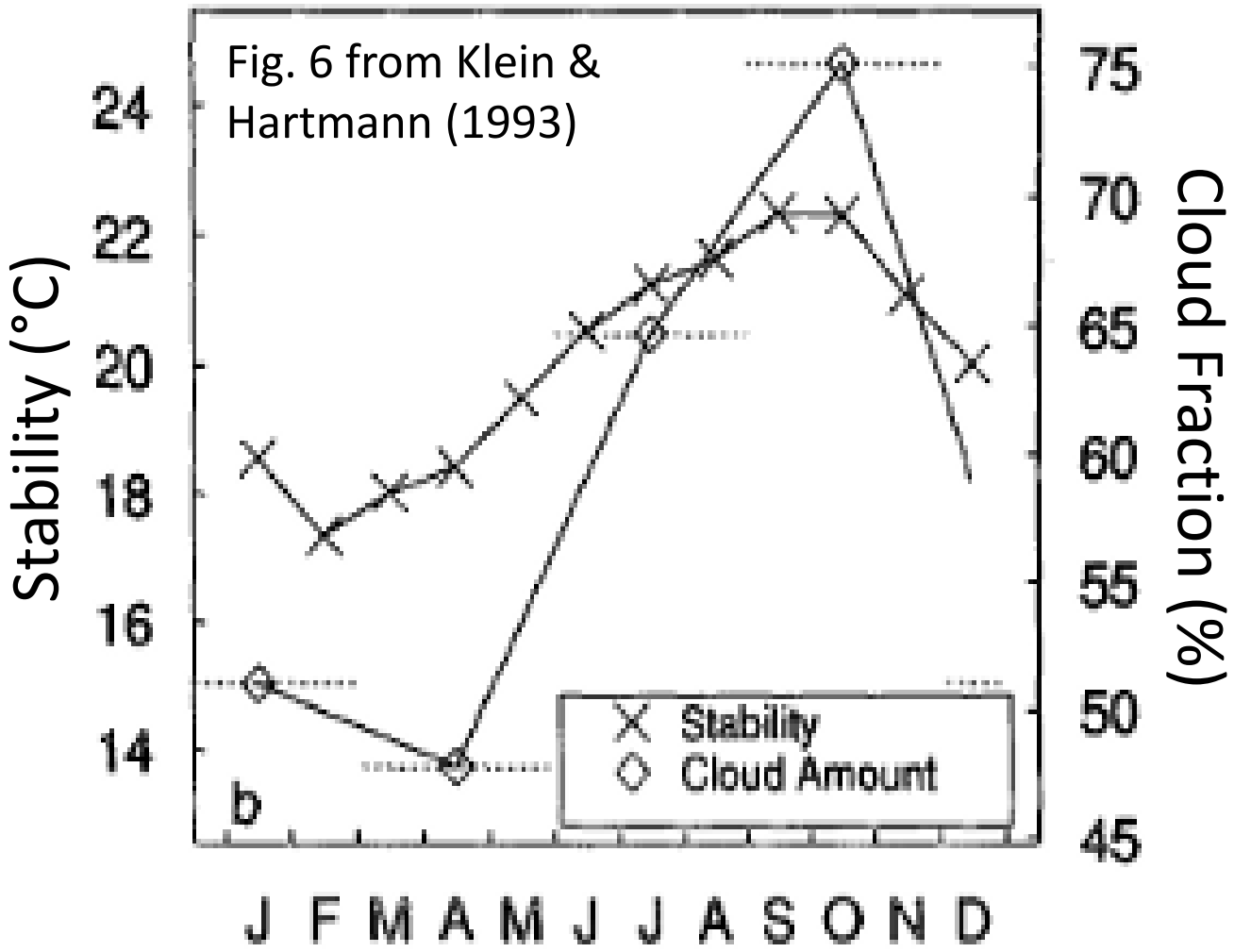
Annual Cycle of Cloud Fraction in the SE Atlantic



Cloud Fraction Variability Interannual

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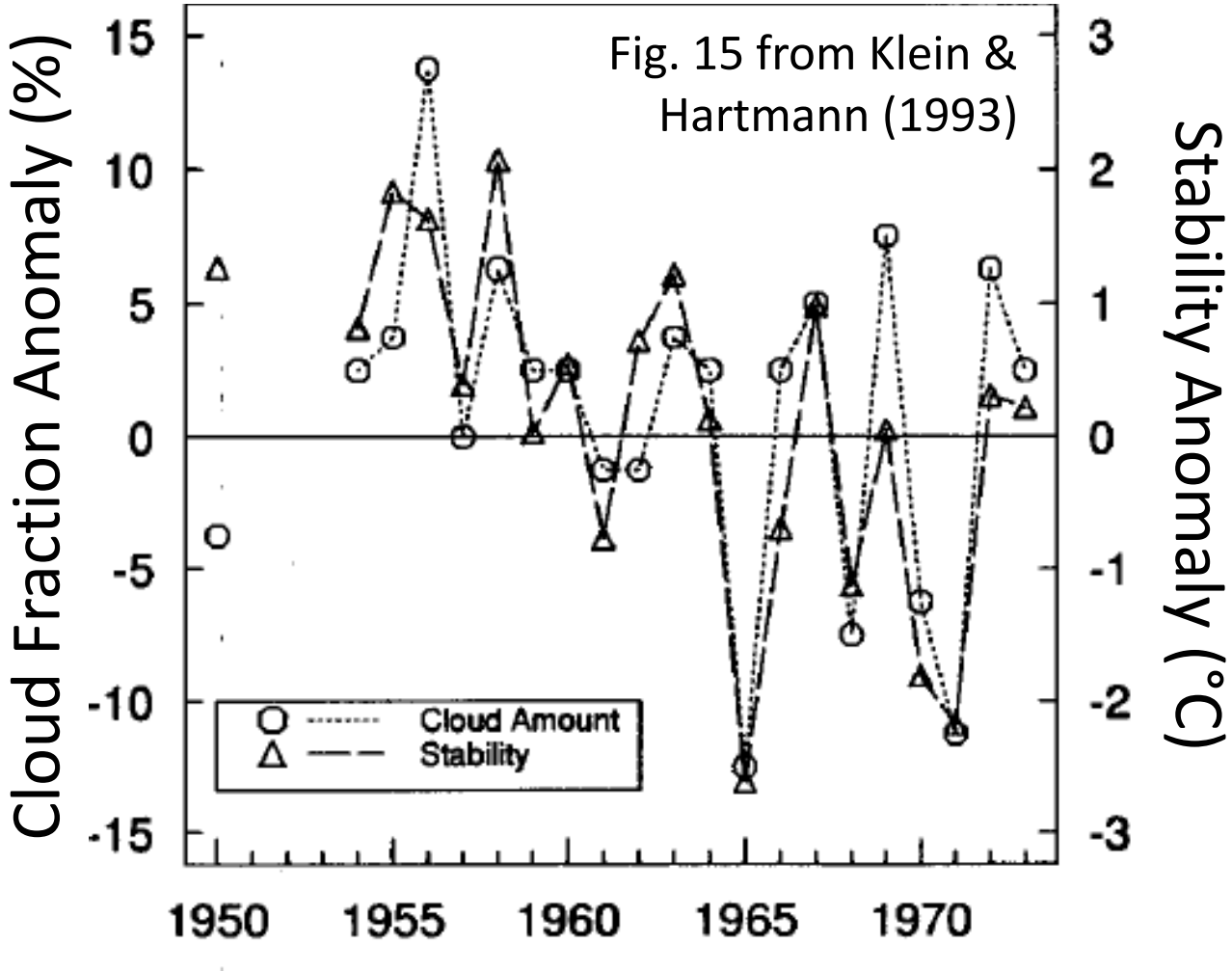
Interannual Variability of Cloud Fraction in the NE Pacific



Processes That Modify Stratocumulus Cloud Fraction

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Large Scale

Small Scale

Inversion Strength and Stability

+

Boundary Layer Depth

+

Boundary Layer Mixing

+

Shortwave Heating

+

Precipitation

+

Aerosol Concentrations (-> Precipitation)

Processes That Modify Stratocumulus Cloud Fraction

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~~Inversion Strength and Stability~~

+

Large Scale

Boundary Layer Depth

+

Boundary Layer Mixing

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Shortwave Heating

+

Precipitation

Small Scale

+

~~Aerosol Concentrations (-> Precipitation)~~

Processes That Modify Stratocumulus Cloud Fraction

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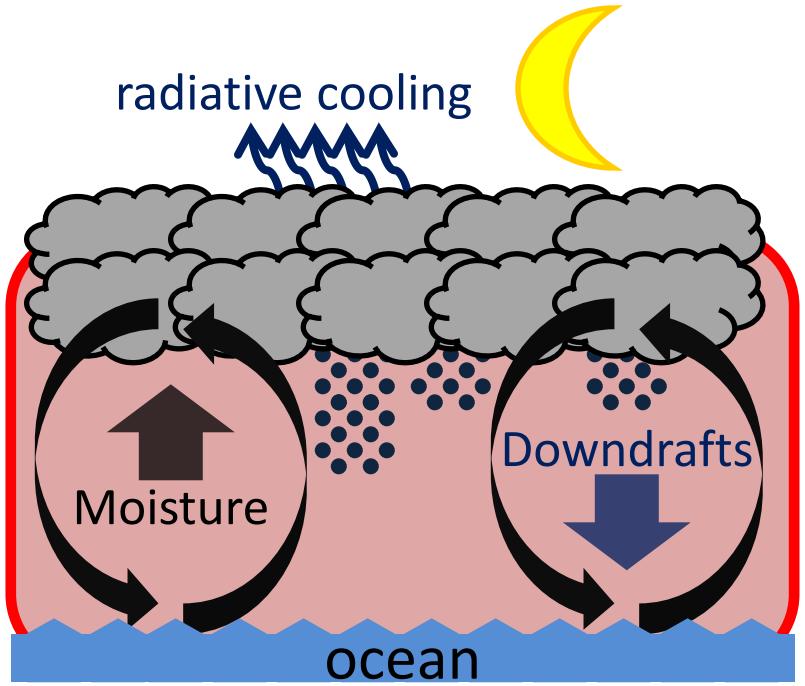
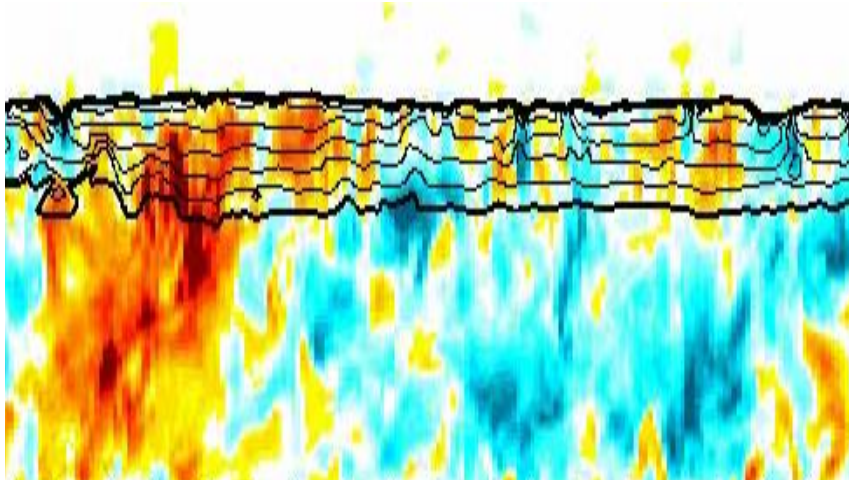
Night



The boundary layer is coupled through cloud top radiative cooling and cellular convection.



25 km

Downdraft Updraft

[Awesome] Simulations courtesy of B. Stevens (Max-Planck)

Processes That Modify Stratocumulus Cloud Fraction

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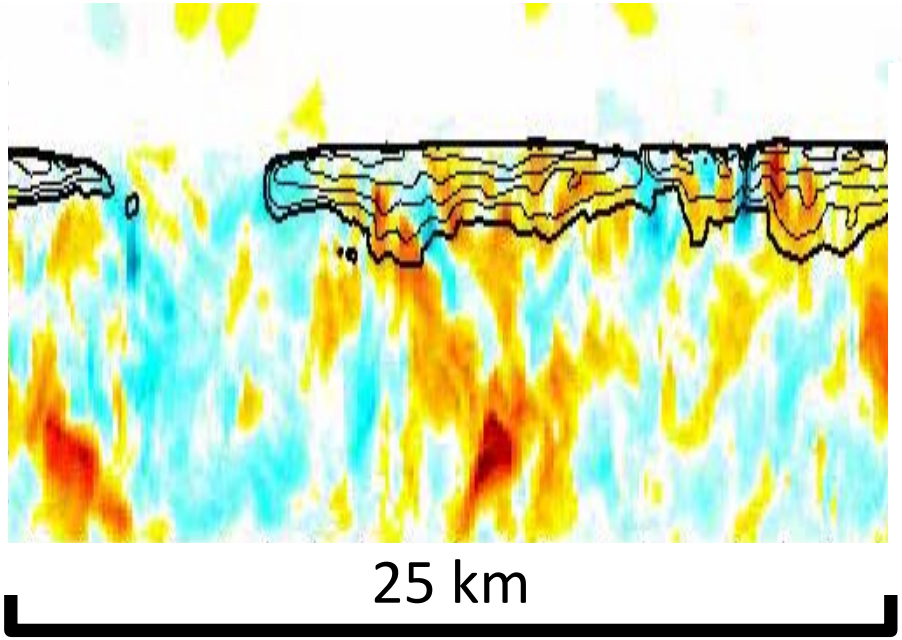
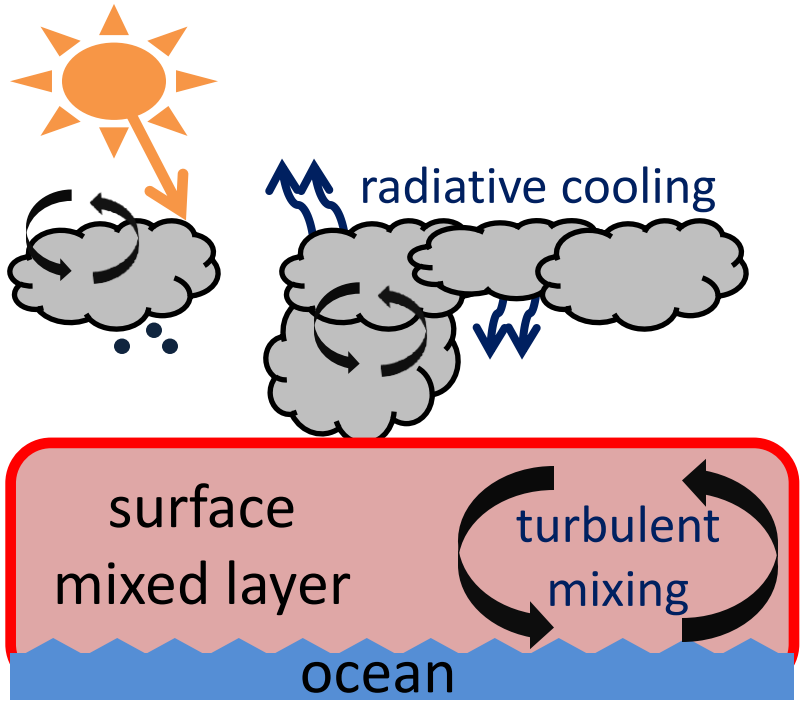
Day





The surface mixed layer is less strongly coupled to the cloud deck.

[Awesome] Simulations courtesy of B. Stevens (Max-Planck)

Processes That Modify Stratocumulus Cloud Fraction

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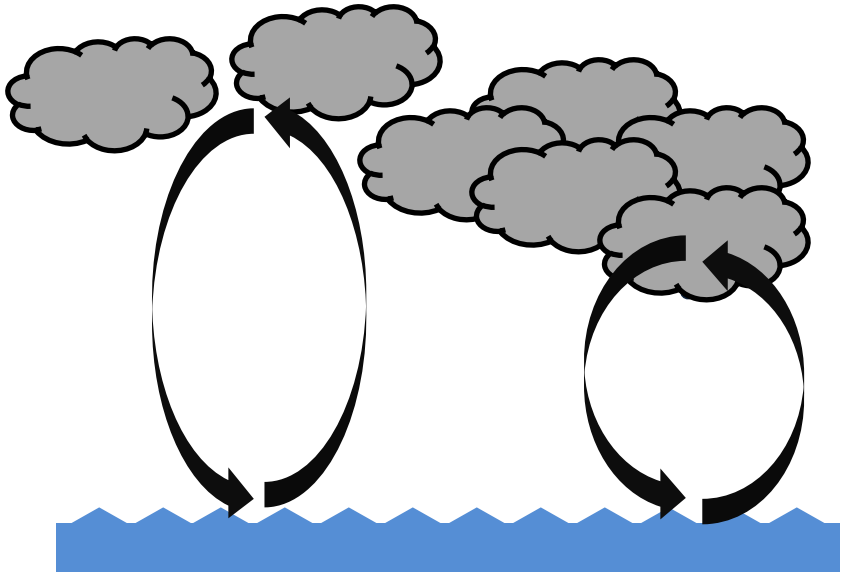
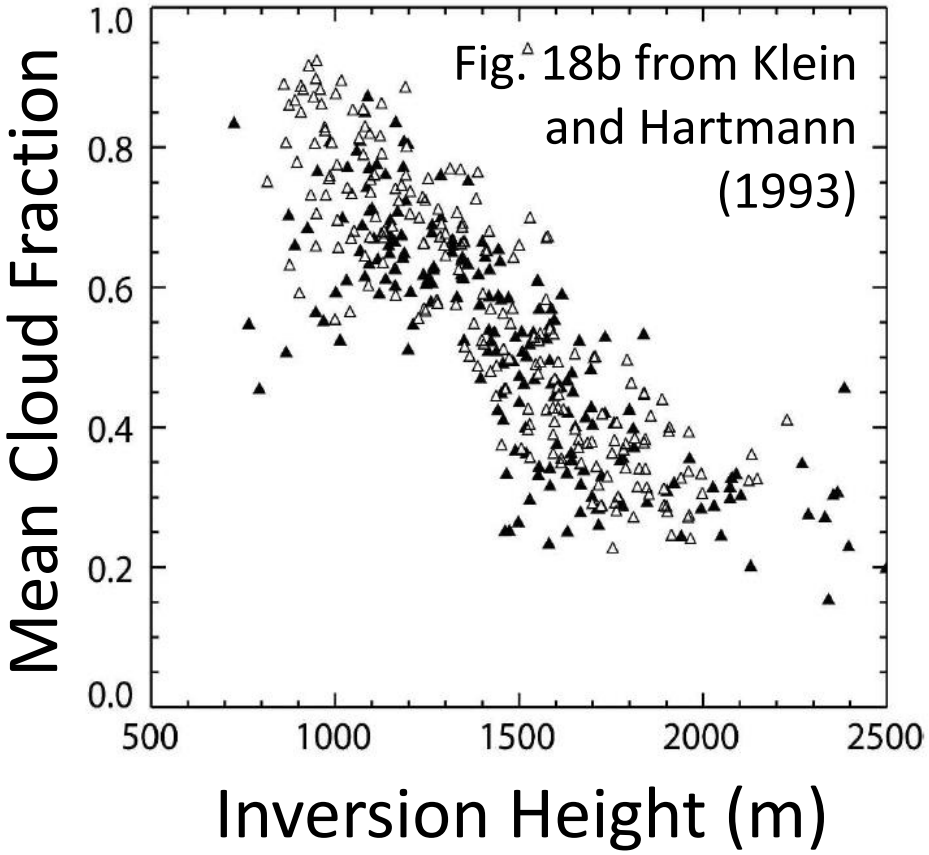
Boundary Layer Depth (Inversion Height)



A deeper boundary layer requires stronger turbulent overturning to maintain coupling between the cloud and the moist surface layer.



Processes That Modify Stratocumulus Cloud Fraction

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Precipitation (Drizzle)

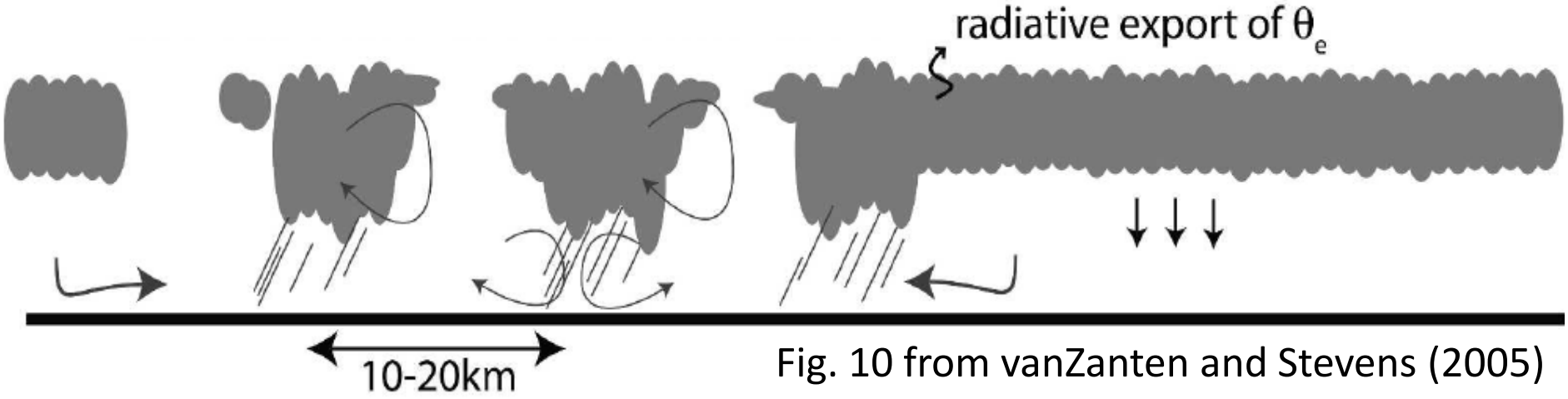

Fig. 10 from vanZanten and Stevens (2005)

Precipitation:

- Subcloud evaporation combined with in-cloud latent heating can stabilize the subcloud layer
- Cold pools and drizzle outflows can act to reduce or enhance subcloud mixing and cloud fraction

Processes That Modify Stratocumulus Cloud Fraction

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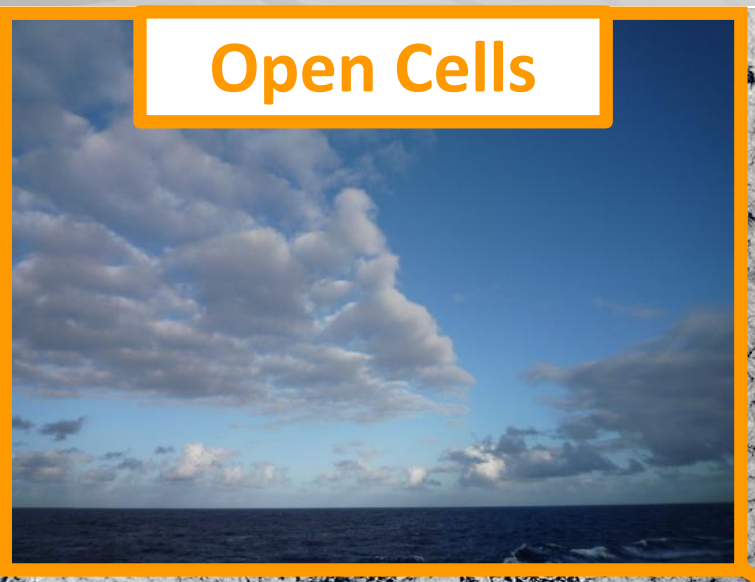

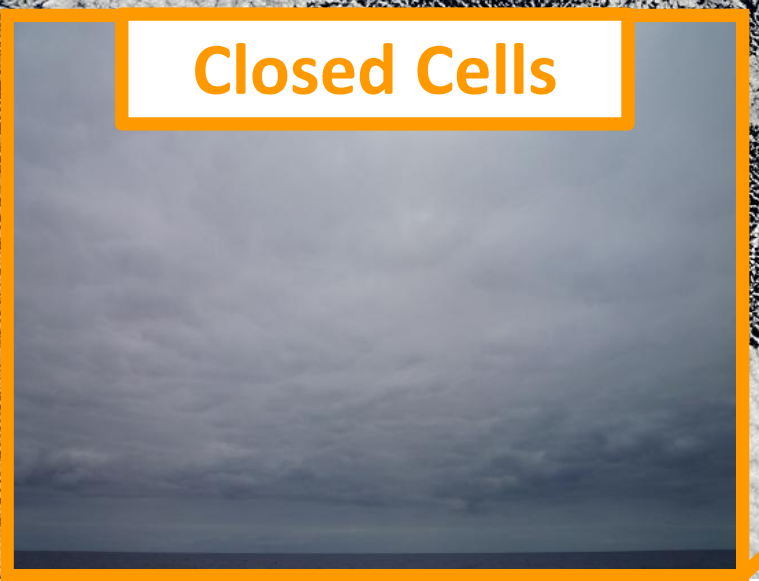

~100 km

MODIS image courtesy of R. Wood

Pockets of Open Cells (POCs)

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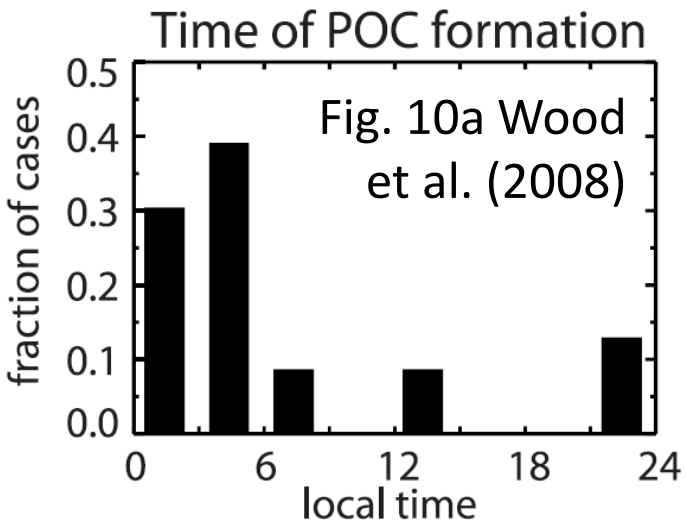
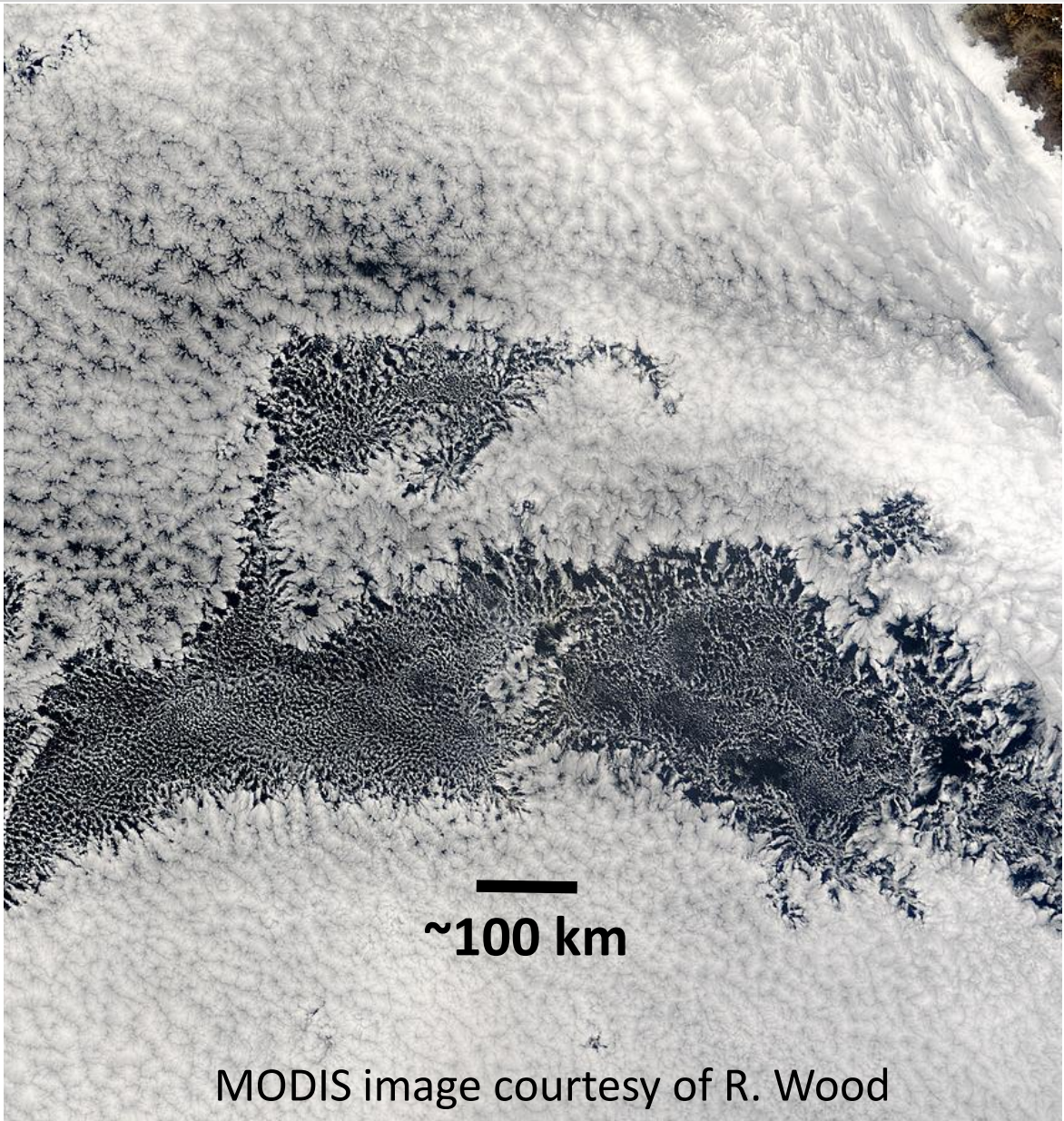
Wood et al. 2008

- Found 23 POC formation events during Sep-Oct 2001
- 80% of the POCs classified formed overnight





MODIS image courtesy of R. Wood

Pockets of Open Cells (POCs)

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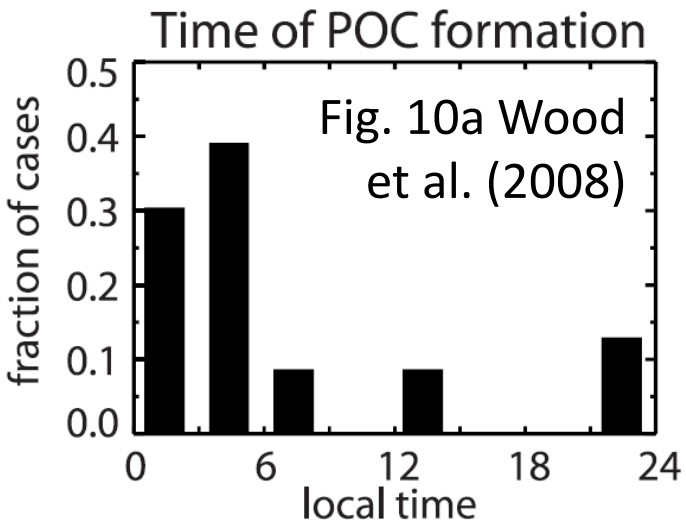
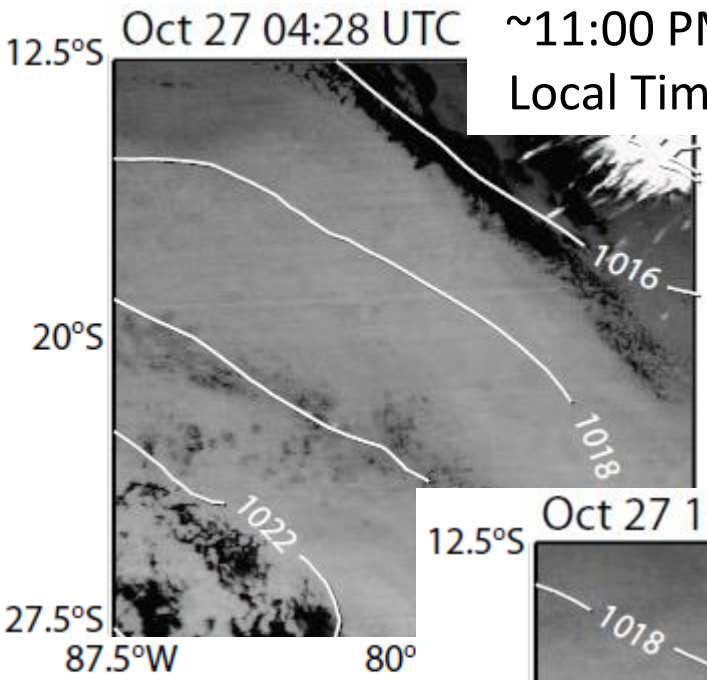
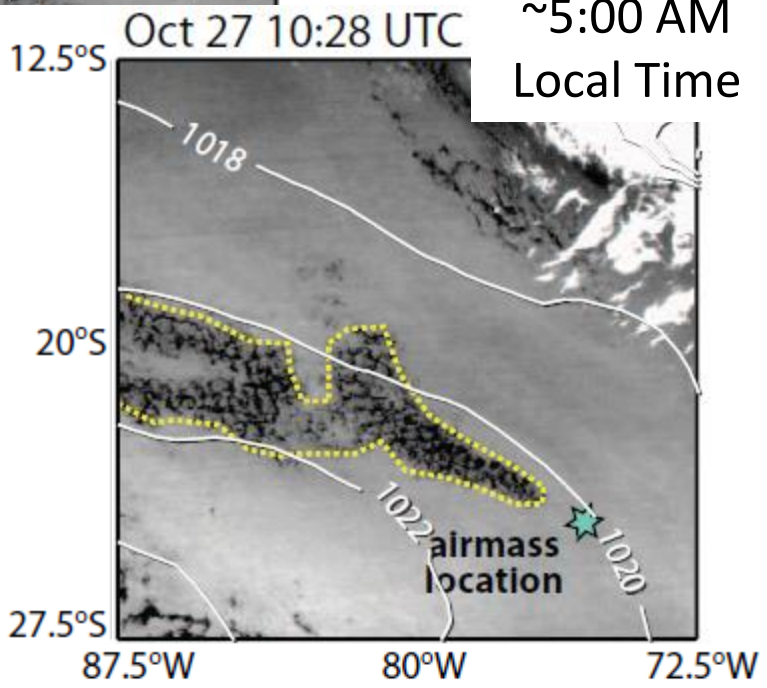




~11:00 PM Local Time

Adapted from Fig. 2 of Wood et al. (2010)

~5:00 AM Local Time



Pockets of Open Cells (POCs)

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Wood et al. 2008

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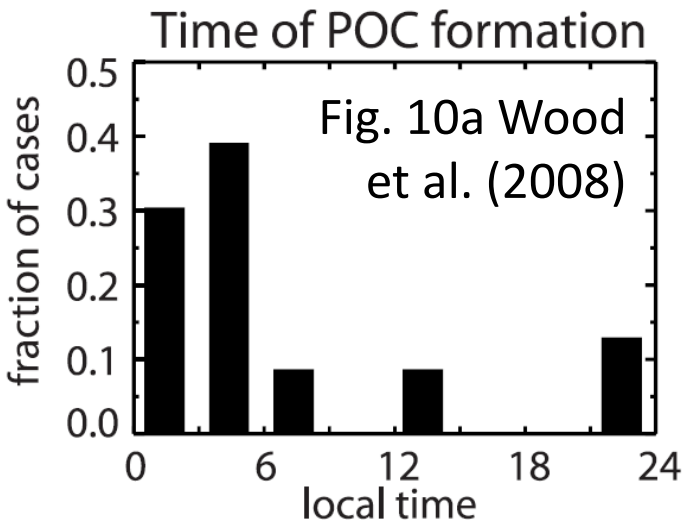

POCs were associated with a change in cloud fraction overnight from > 90% to less than 60%.

POCs have been linked to:

Precipitation

Aerosols

Gravity waves

Density currents

Boundary layer depth

Synoptic waves

What are the Important Processes on Diurnal Time Scales?

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~~Inversion Strength and Stability~~

+

Boundary Layer Depth

+

Boundary Layer Mixing

+

Shortwave Heating

+

Precipitation

+

~~Aerosol Concentrations (-> Precipitation)~~

Are POCs Important?

VOCALS-REx

The investigation of POCs and the processes that lead to POC formation was one of the driving forces behind the VOCALS program.

"The frequency and climatic importance of POCs remains poorly characterized." – Mechoso et al. (2014)

How Different are the Various Subtropical Stratocumulus Regions?

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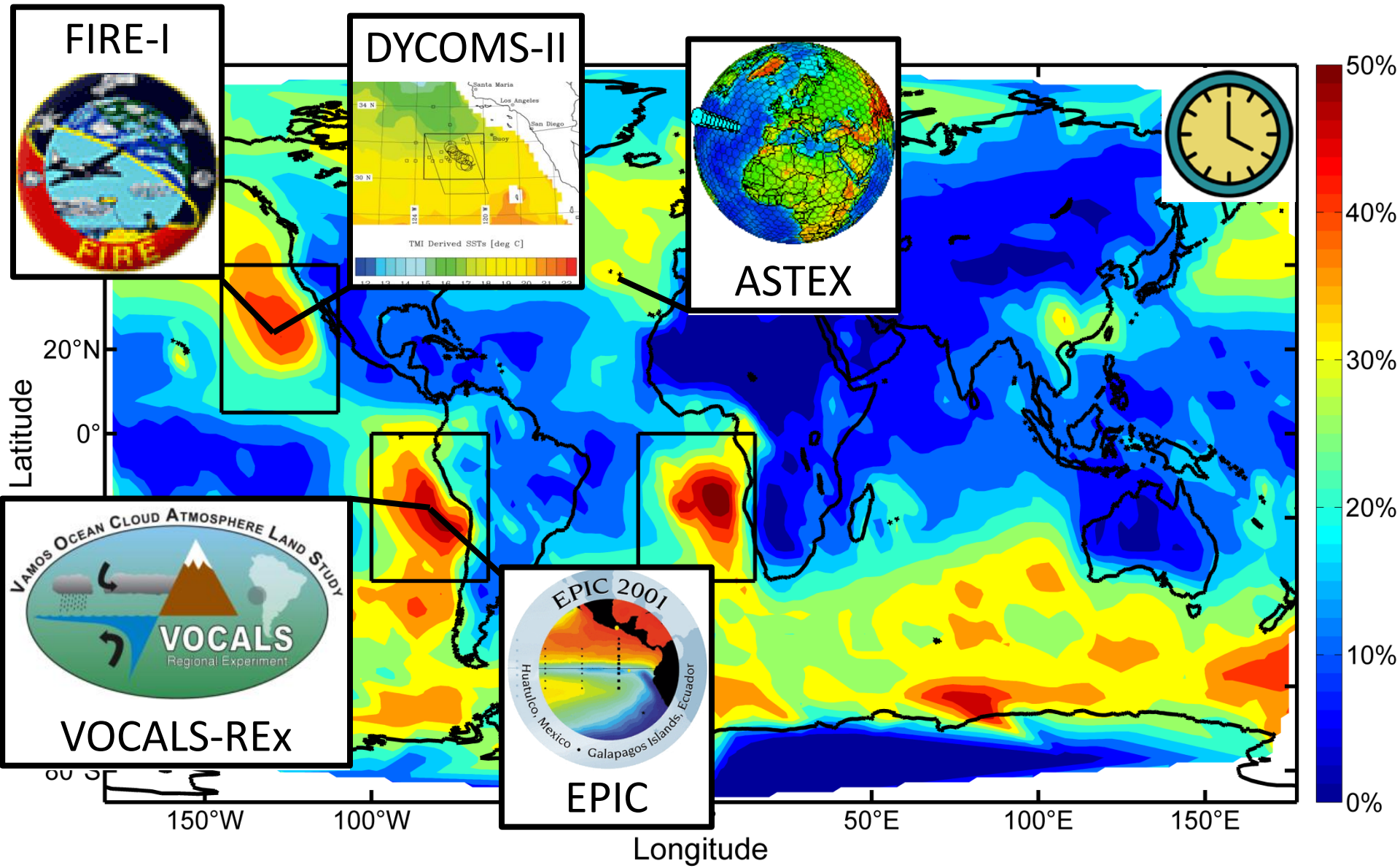

Observing Stratocumulus Clouds

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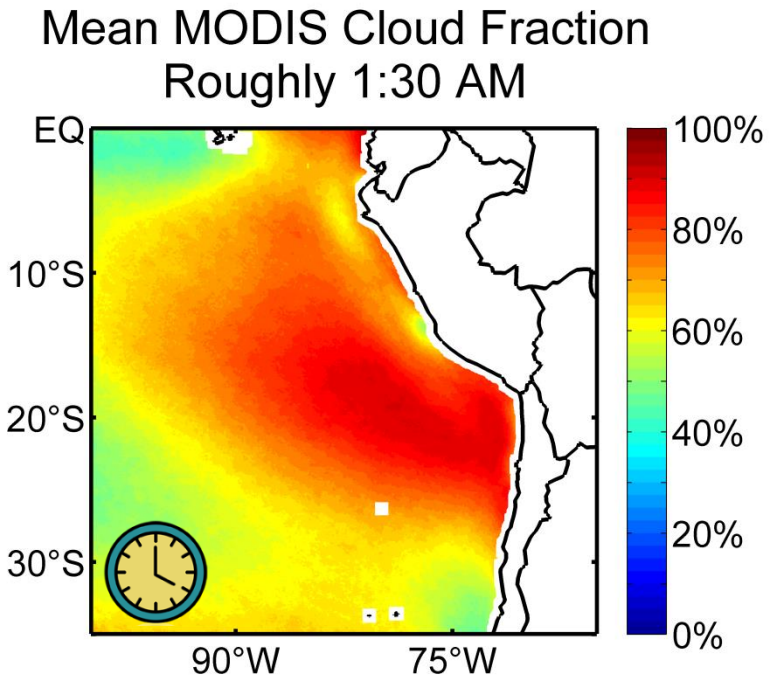
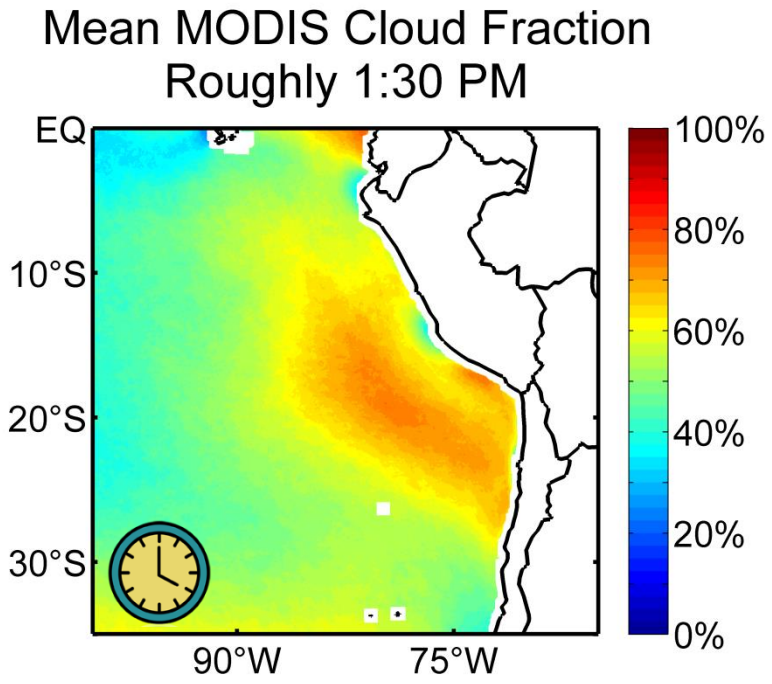
Visible satellite imagery has a high spatial resolution and rapid update times but is only available during the day making it unsuitable to study the diurnal cycle.



Stuff Happens



MODIS cloud fractions provide measurements during the day and at night, but are only available twice per day.

Observing Stratocumulus Clouds

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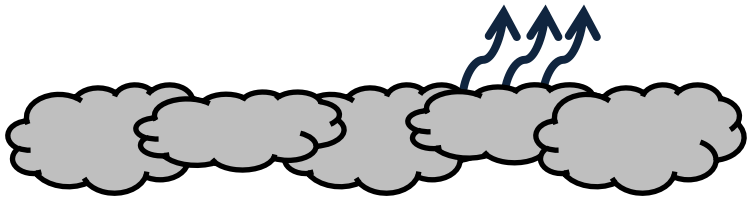
It is possible to observe the clouds across the diurnal cycle by measuring the radiation they emit.

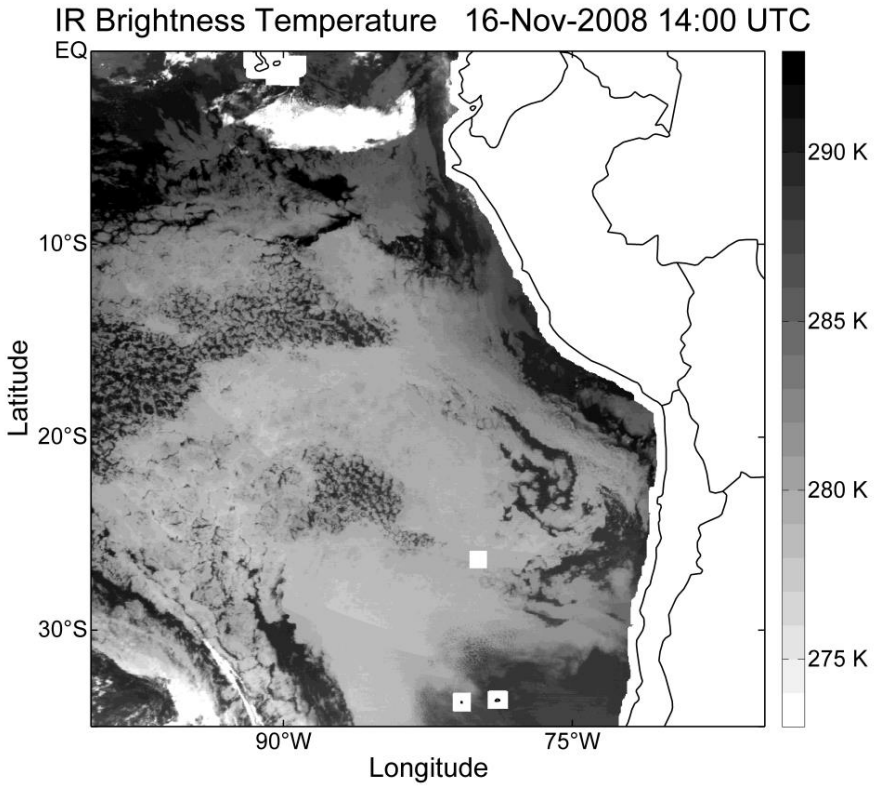
$$u^* = \varepsilon\sigma T^4$$

u^* = Irradiance T = Temperature

σ = Stefan-Boltzmann constant ε = Emissivity



$T_{Ocean} \approx 287$ K $T_{Clouds} \approx 279$ K



Observing Stratocumulus Clouds

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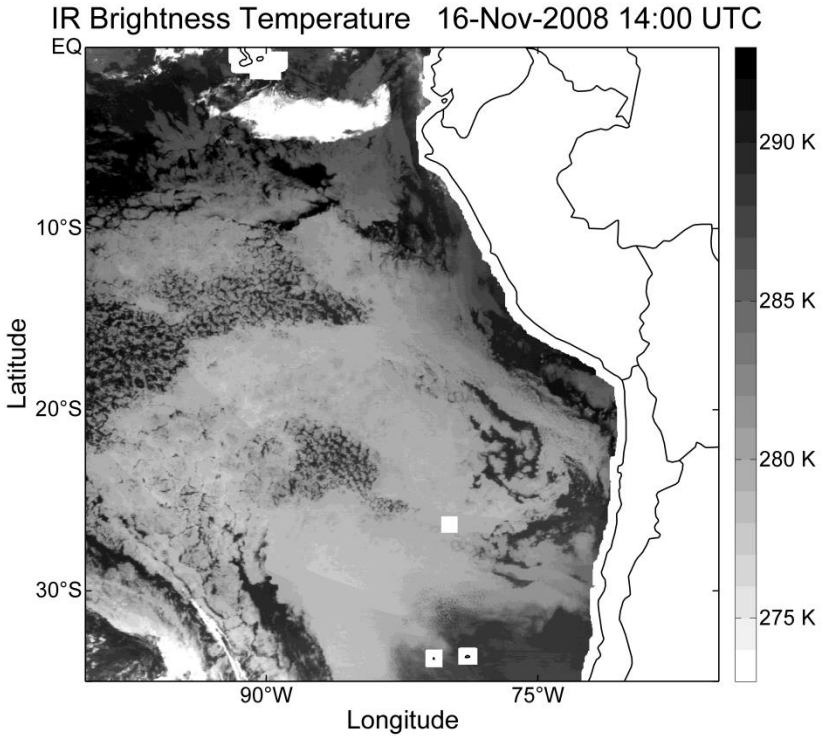
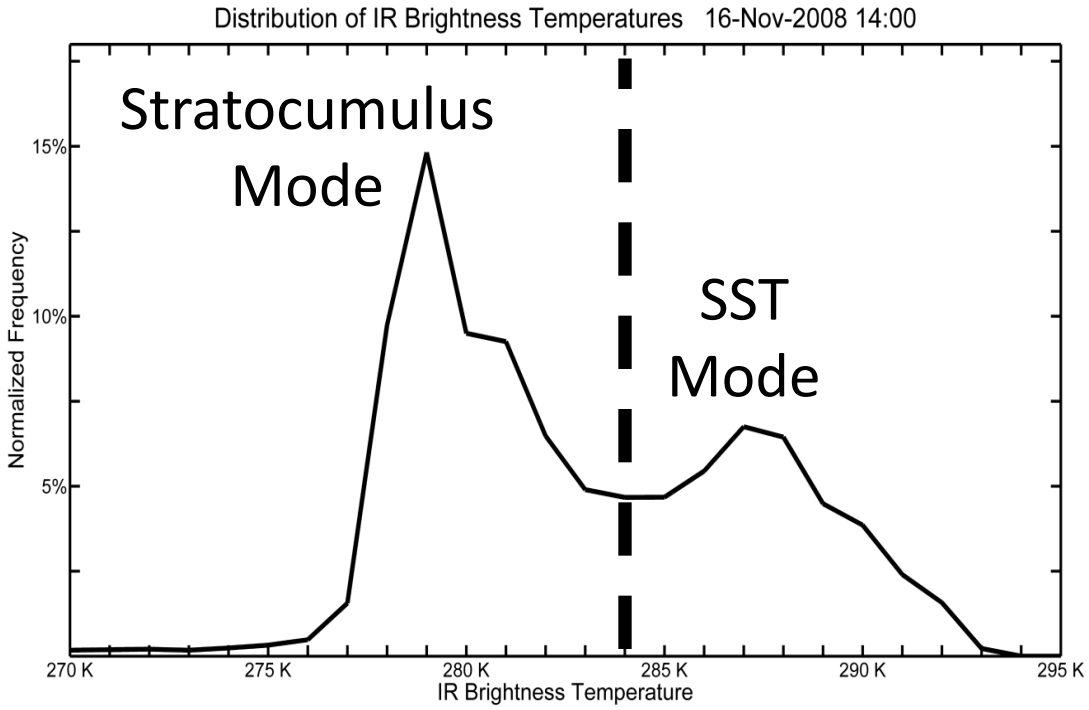


I developed an automated method to separate the two temperature modes. This allows for a pixel-by-pixel classification of either cloud or ocean.



IR Brightness Temperature Dataset

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I take advantage of the NASA/NOAA global merged-IR dataset which brings together IR measurements from multiple geostationary satellites and allows for easy comparison among regions:

- Available from February 2000 onward
- Native spatial resolution of 4 km x 4 km
- **Native temporal resolution of 30 min**
- Available from 60°S-60°N around the globe

Evaluation

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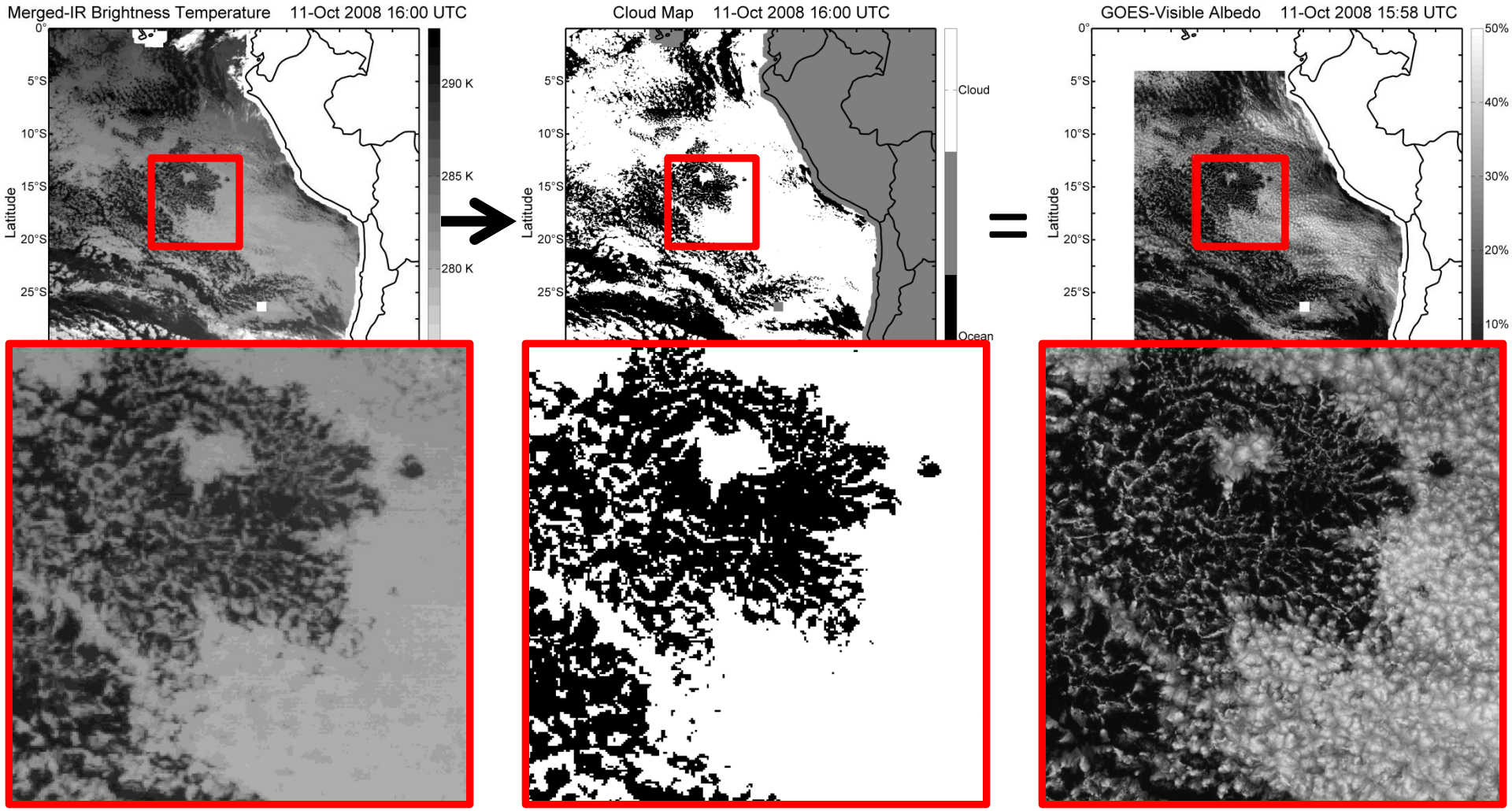
Our cloud maps can be directly compared to visible satellite imagery during daytime scenes…



Evaluation

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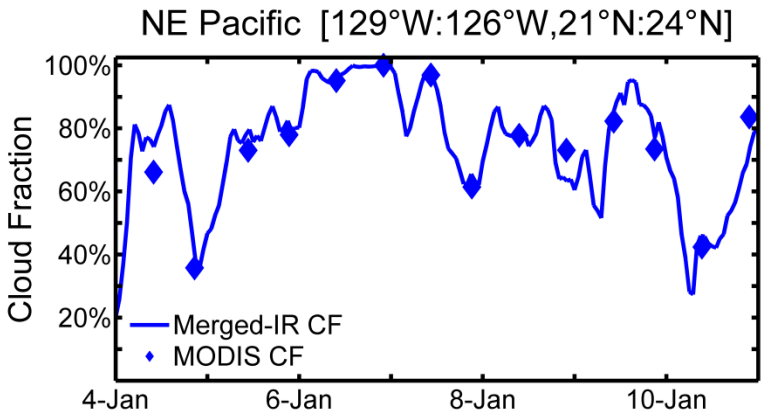
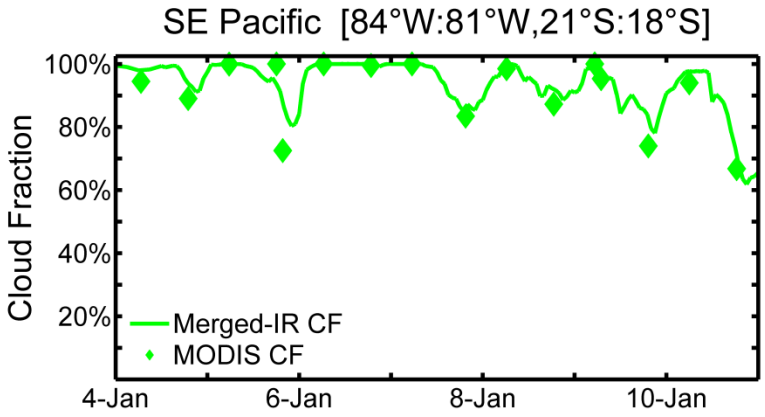
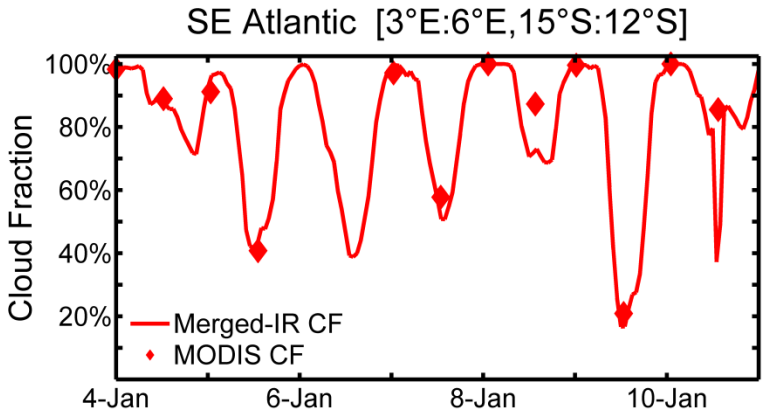
Our cloud fractions can be compared to MODIS cloud fractions calculated for the same regions…







Evaluation

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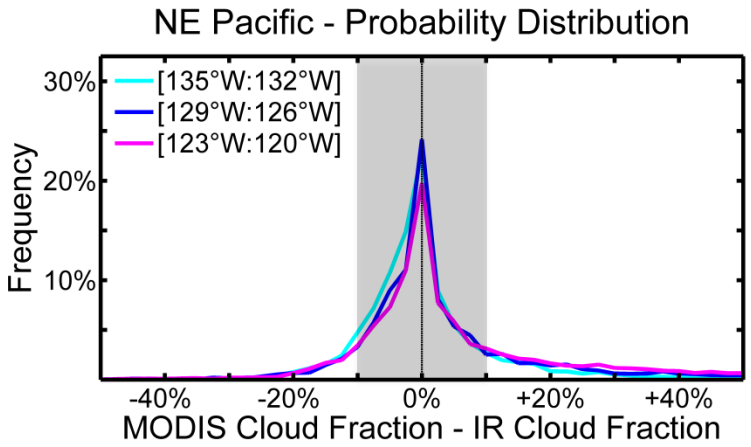
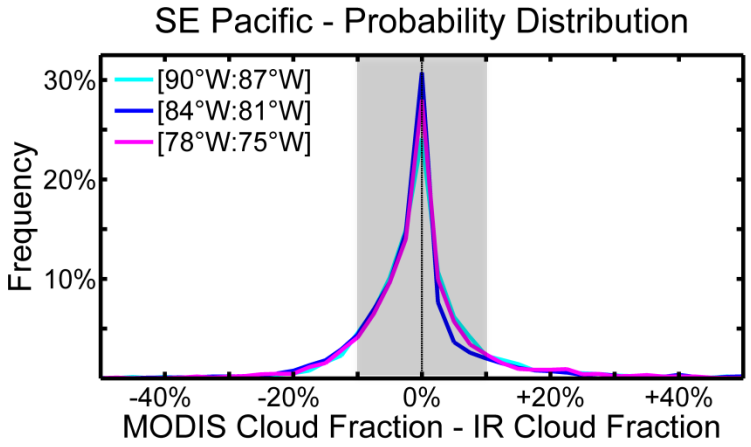


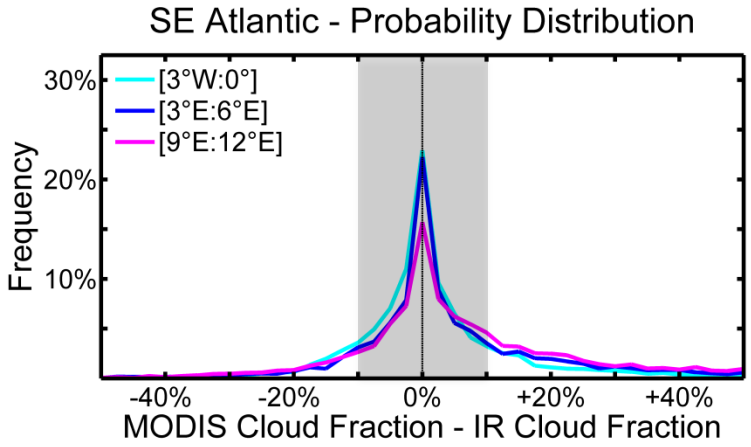
Within +/- 10% of MODIS…

65% of the time in the NE Pacific

80% of the time in the SE Pacific

70% of the time in the SE Atlantic





Data Limitations

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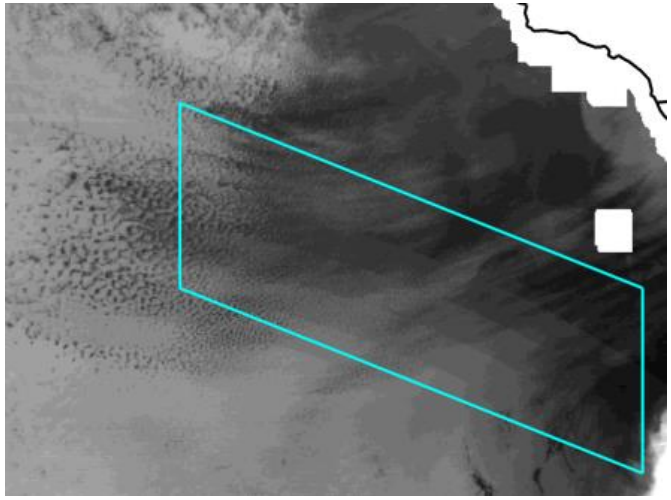
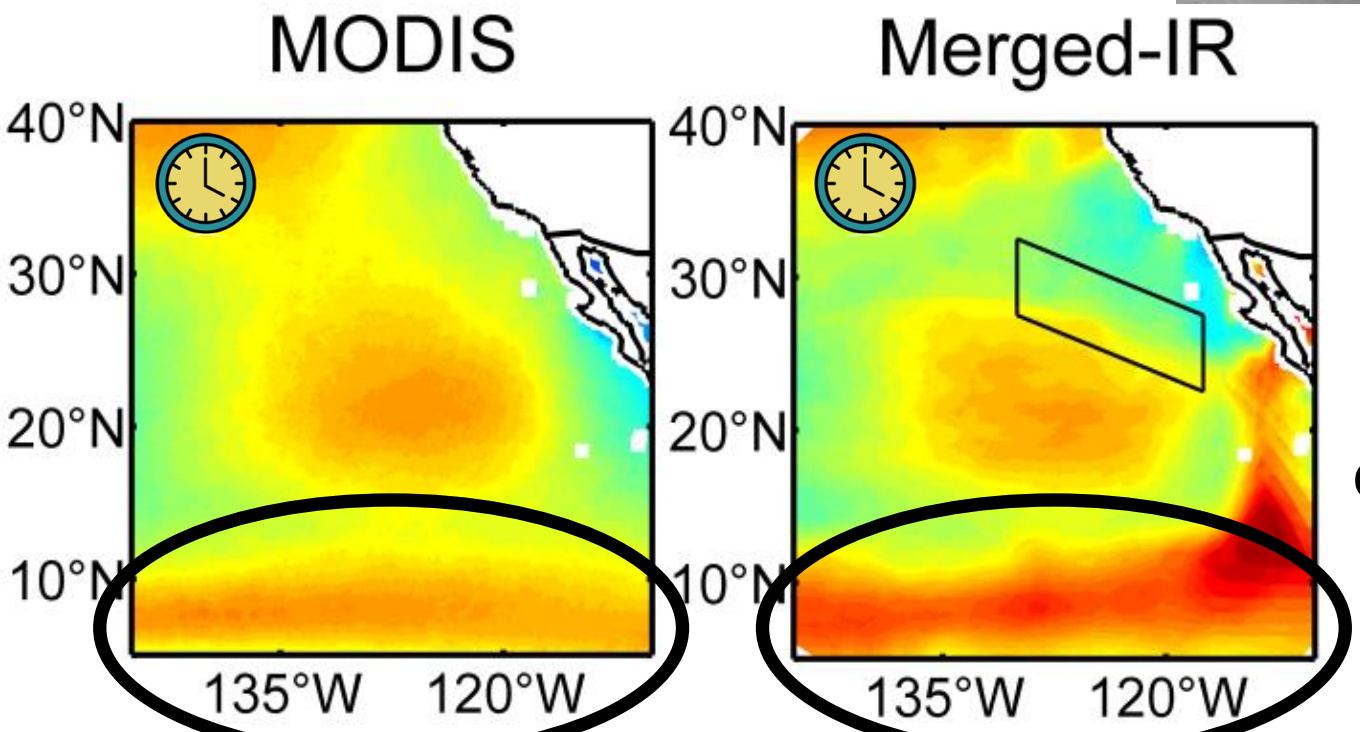
There is a region in the California region where the viewing-angle correction built into the native IR brightness temperature data is flawed…





The algorithm was designed to work in regions of predominantly low clouds…

Results – Diurnal Cycle of Cloud Fraction

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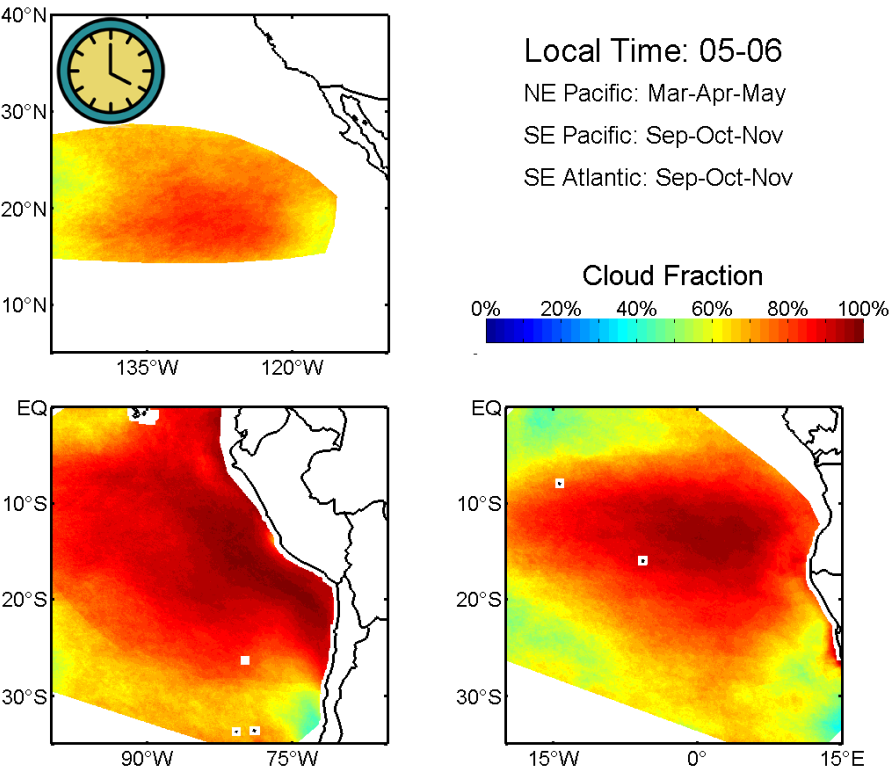
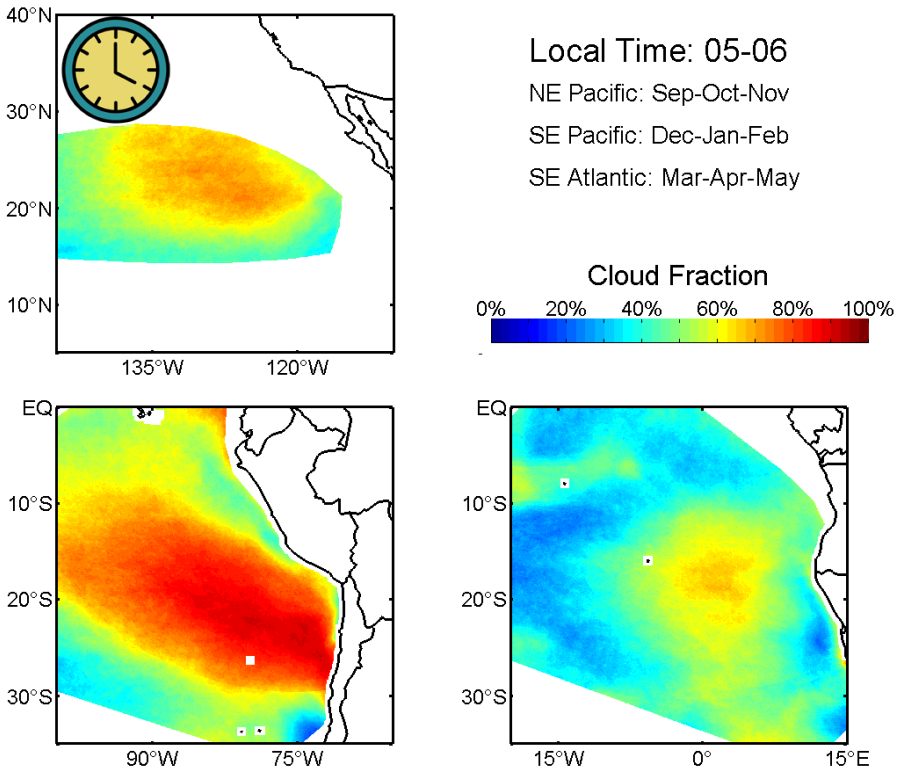
Peak Season of Cloudiness



Minimum Season of Cloudiness



Earlier breakup of the cloud and larger amplitude diurnal cycles are observed in low cloud fraction regions and in deeper boundary layers.

Results – Diurnal Cycle of Cloud Fraction

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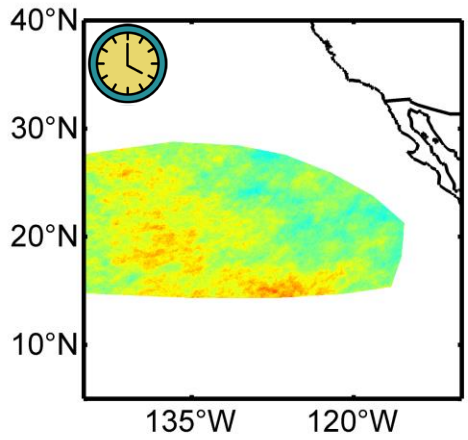
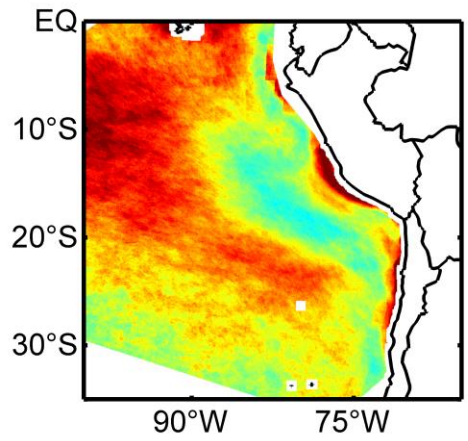
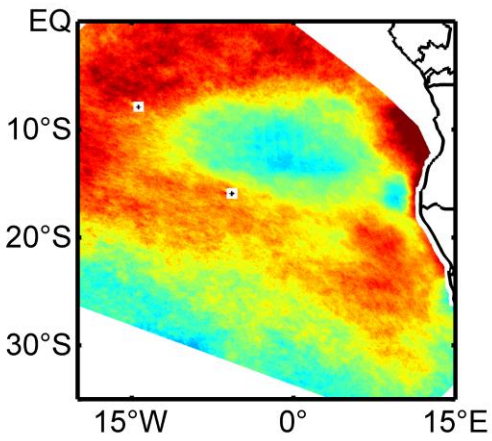
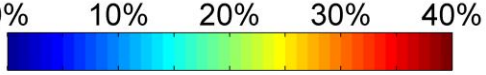
Maximum – Minimum Hourly Mean Cloud Fraction

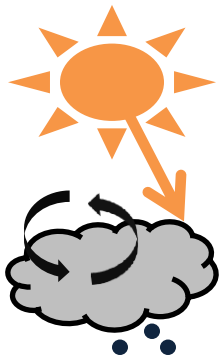




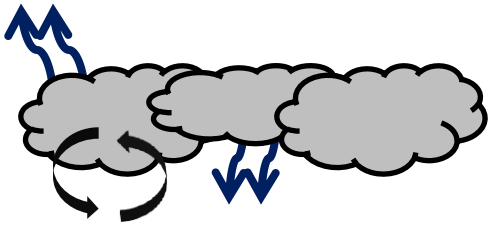


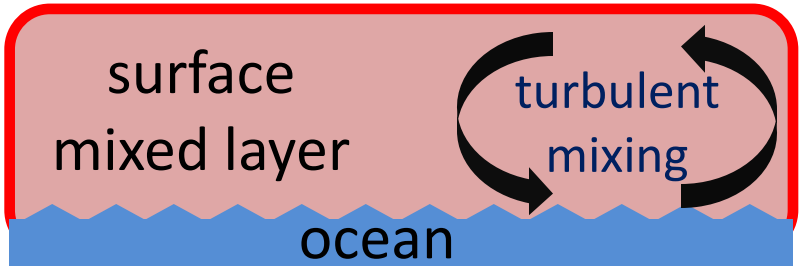
Peak Season
Diurnal Cycle Amplitude





Radiative Cooling
= f(Cloud Fraction)





The reduction in longwave cooling with lowered cloud fractions creates a positive feedback on cloud breakup (i.e. Nicholls and Turton 1986, etc.)

Figure Explanation

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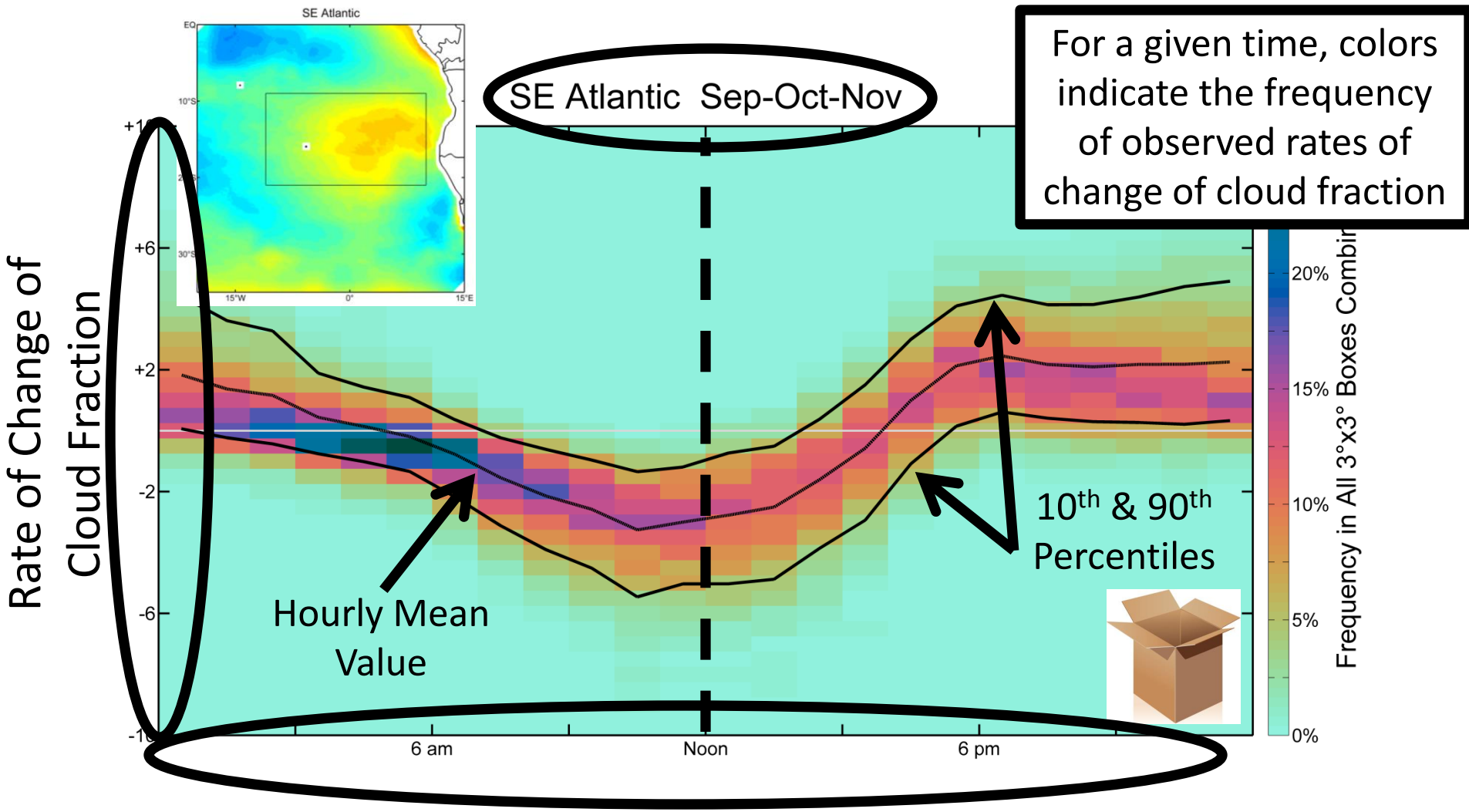
Shown is the frequency distribution of the rate of change of cloud fraction over the entire region:



Results – Distributions of the Rate of Change of Cloud Fraction

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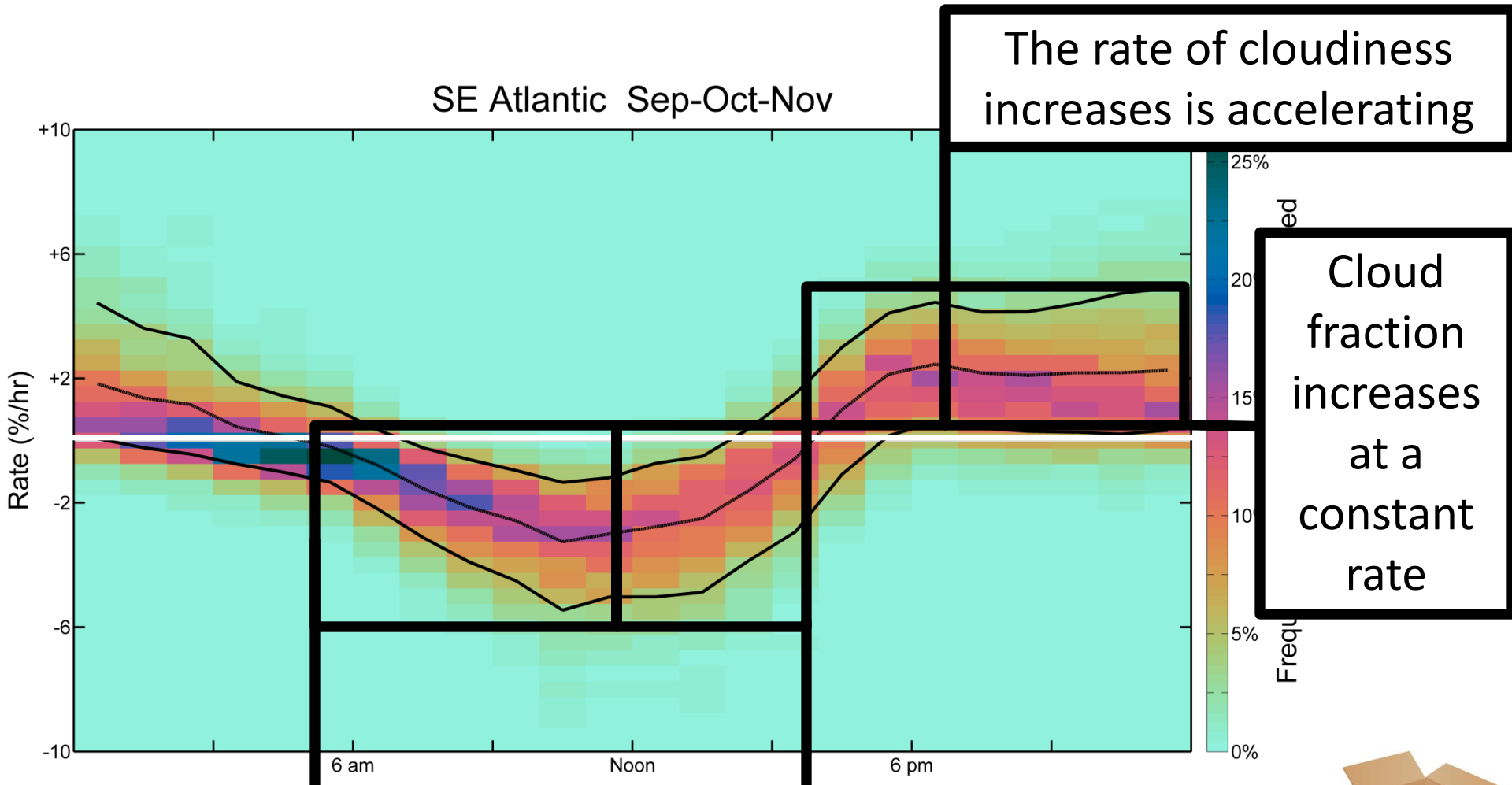

The rate of cloudiness increases is accelerating

Cloud fraction increases at a constant rate

Rate of cloud breakup accelerates

Cloud fractions are still decreasing but at a slower rate

Results – Distributions of the Rate of Change of Cloud Fraction

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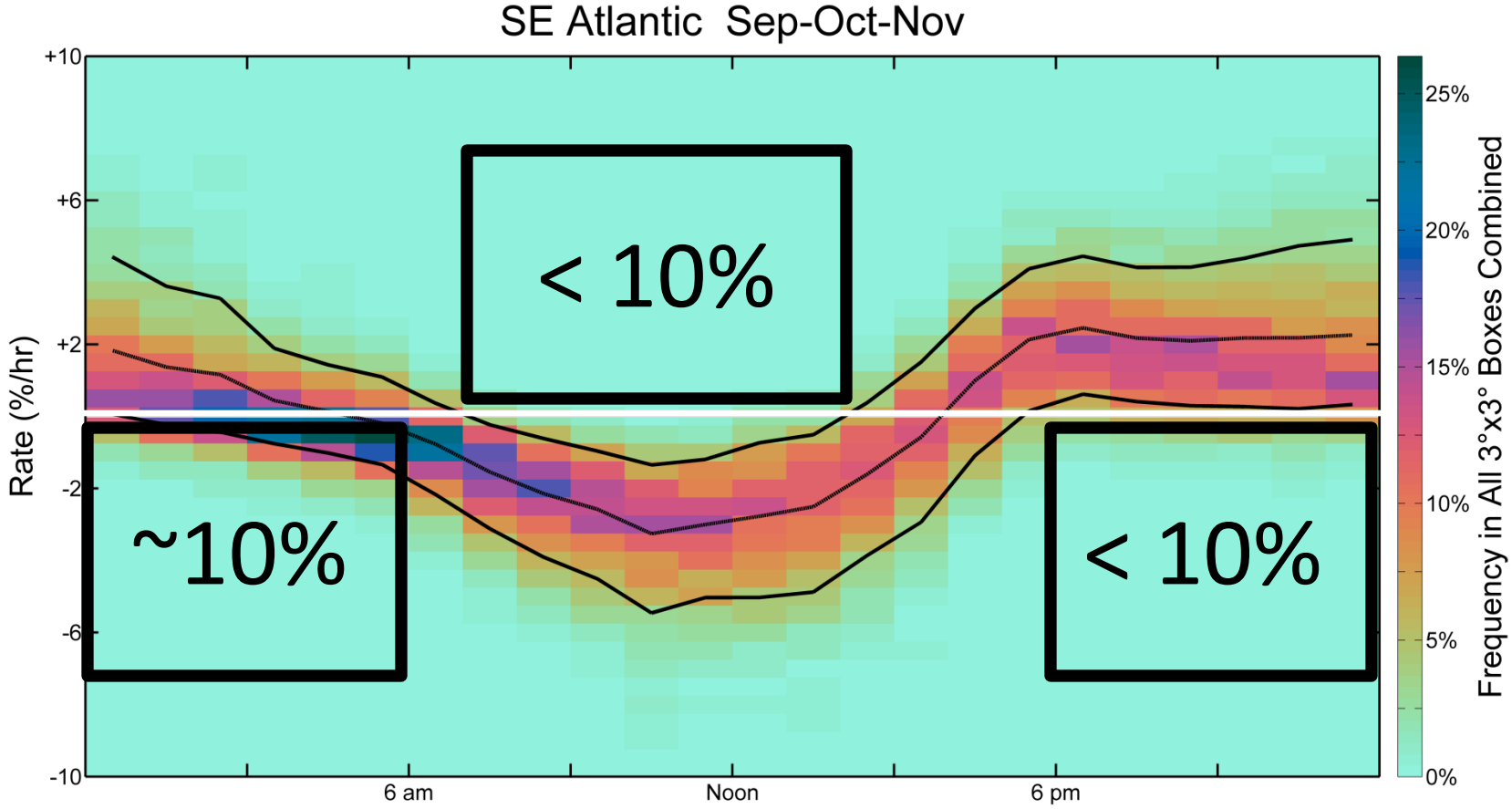

There are very few cases of negative rates of change overnight or positive rates of change during the day.

What is a Typical Change in Cloud Fraction Across the Diurnal Cycle?

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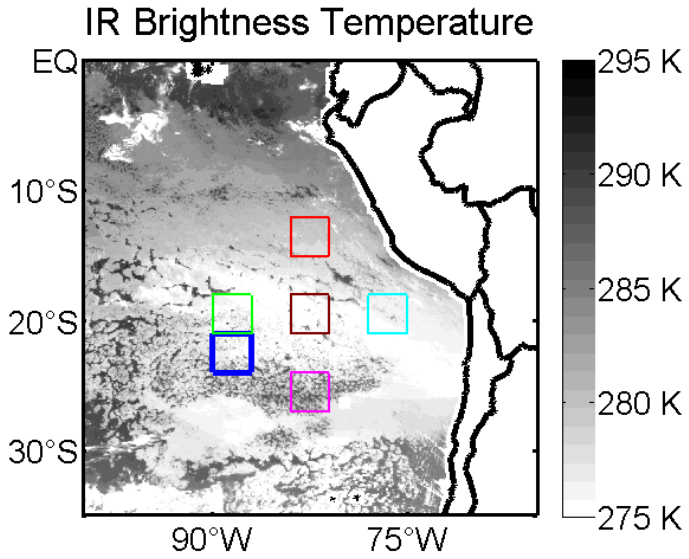
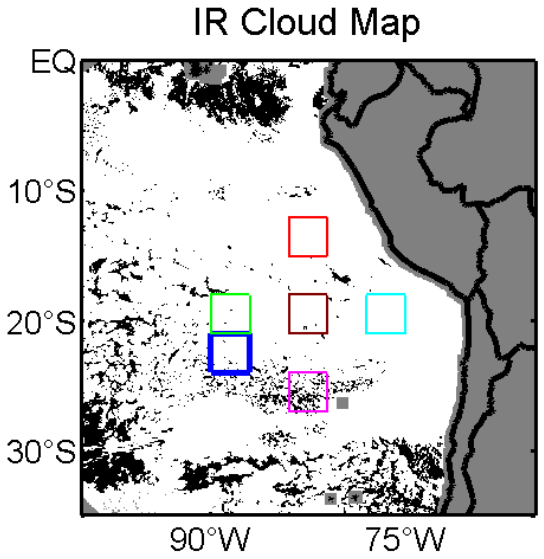
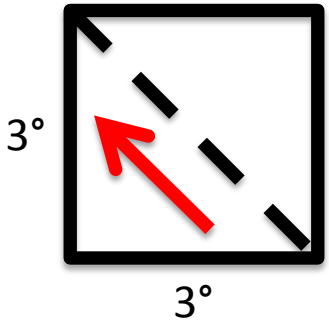
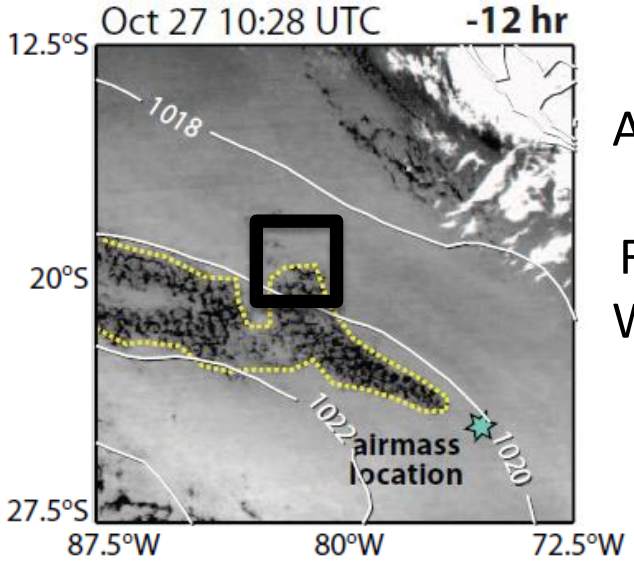




Look at the daytime (6 am – 6 pm) and overnight (6 pm – 6 am) change in cloud fraction in 3° x 3° boxes…



5 m s^{-1} x 12 hr ≈ 215 km
Diagonal = 330 km



Adapted from Fig. 2 of Wood et al. (2010)

Distribution of Net Daytime Cloud Fraction Changes

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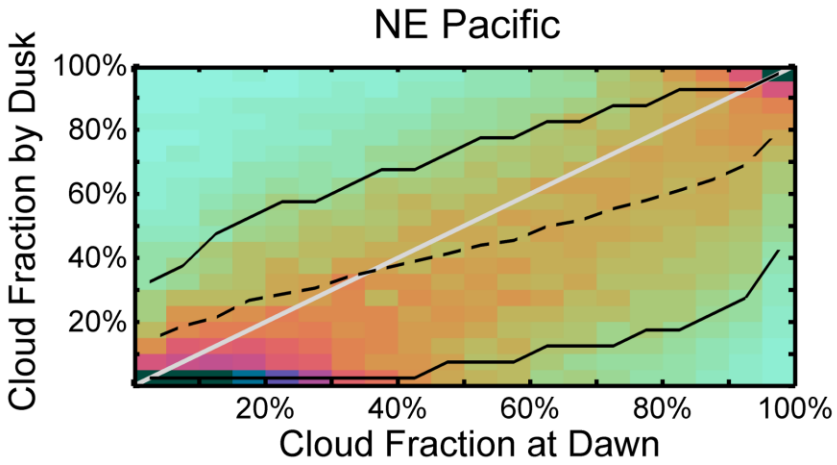
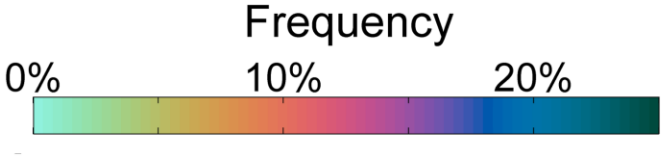
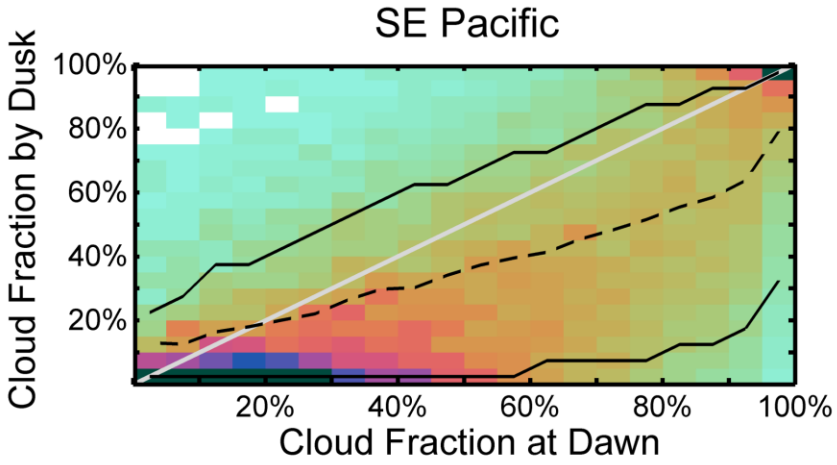
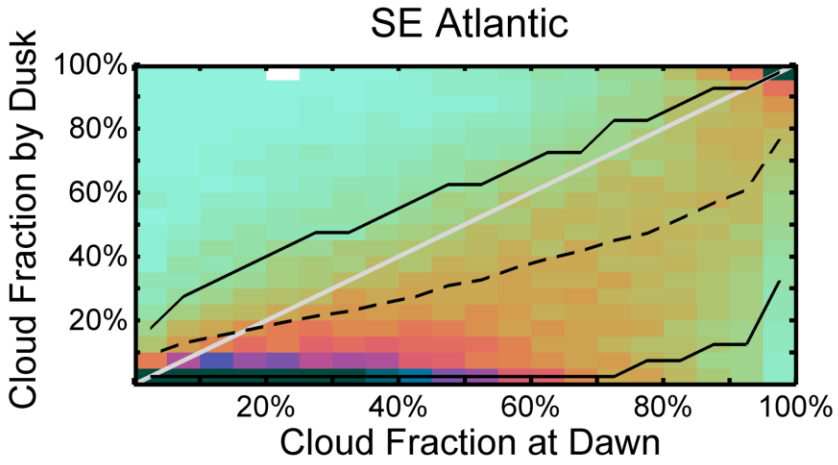
Day









Dawn = 6:00 AM and Dusk = 6:00 PM

Distribution of Net Daytime Cloud Fraction Changes

Pacific Northwest
NATIONAL LABORATORY
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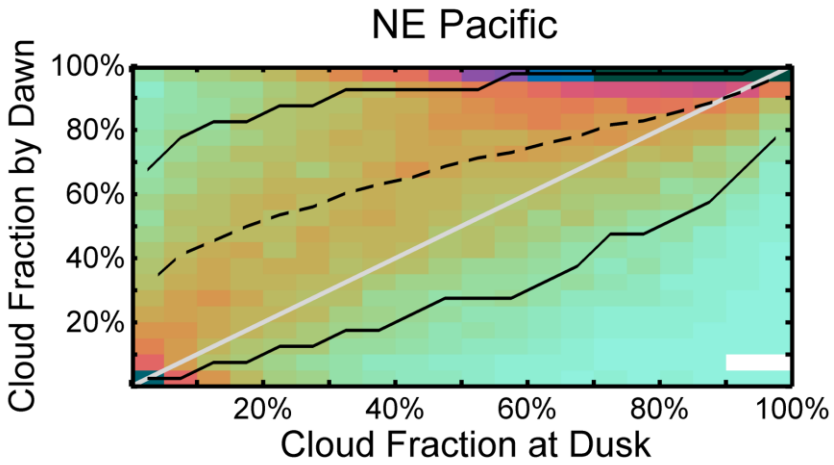
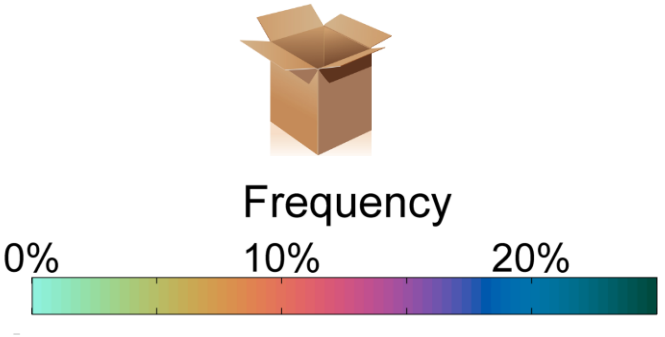
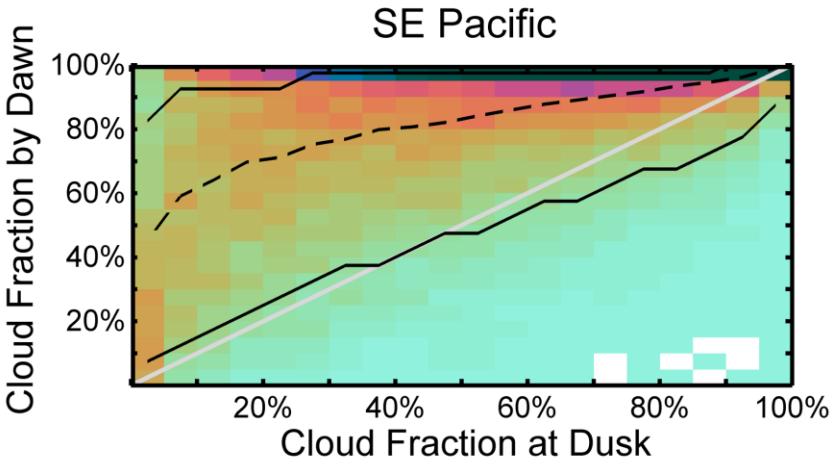
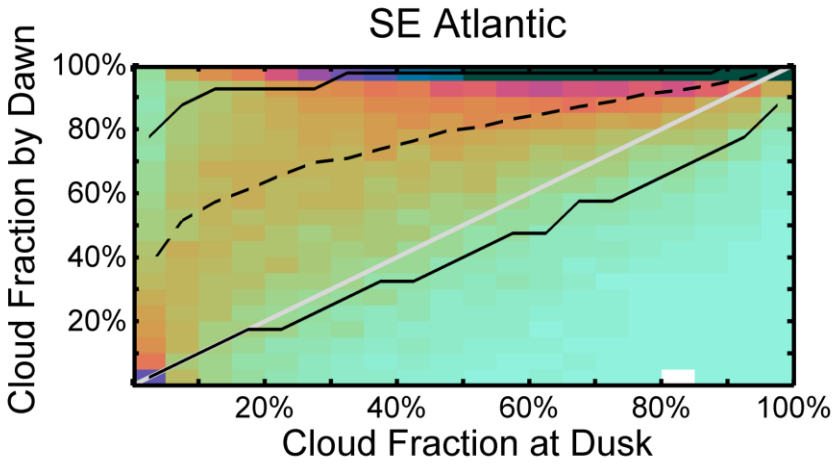
Night









Dawn = 6:00 AM and Dusk = 6:00 PM

Total Overnight Samples in the SE Pacific & SE Atlantic

~~N = 133,062 3° x 3° Boxes~~

Cloud Fraction ≥ 90% at Some Point Overnight

N = 73,867 3° x 3° Boxes

Cloud Fraction Ended ≥ 90%

N = 60,563 (82%)

Cloud Fraction Ended < 90%

N = 13,029 (18%)

Of all samples where cloud fraction reached 90% at some point overnight, less than 1 in 65 had a cloud fraction lower than 60% at sunrise.

Ended < 75%

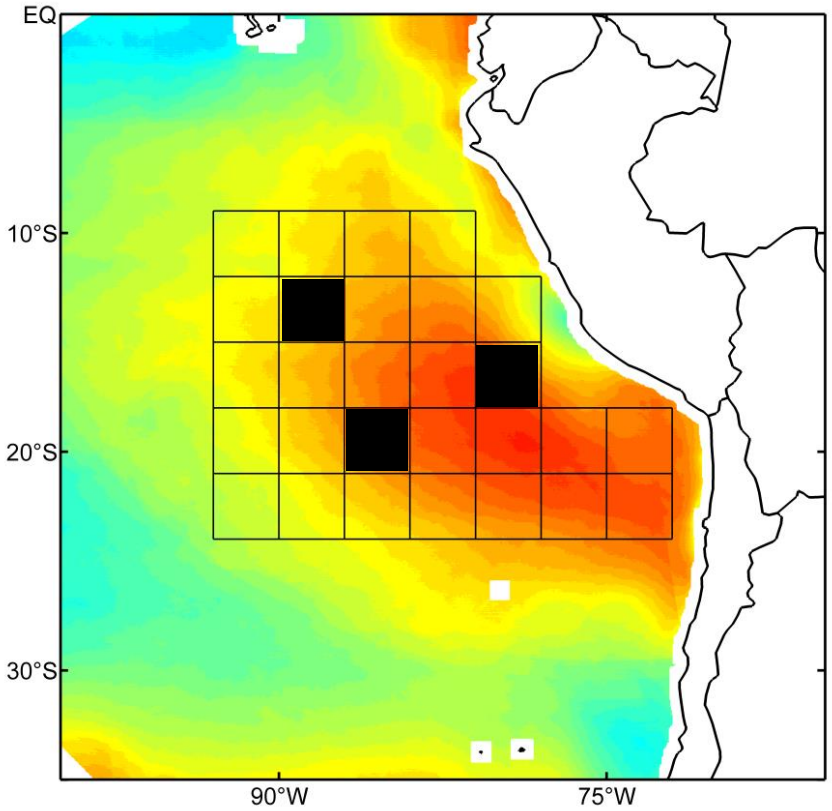
N = 3,578 (4.8%)

Ended < 60%

N = 1,126 (1.5%)

Total Overnight Samples in the SE Pacific & SE Atlantic

N = 133,062 3° x 3° Boxes



This roughly corresponds to 1 ‘POC-like’ transition occurring every third night somewhere within the domain.

Wood et al. (2008) found 23 POCs in 2 months of data.

Of all samples where cloud fraction reached 90% at some point overnight, less than 1 in 65 had a cloud fraction lower than 60% at sunrise.

Relative Magnitudes of Cloud Fraction Decreases – Day vs. Night

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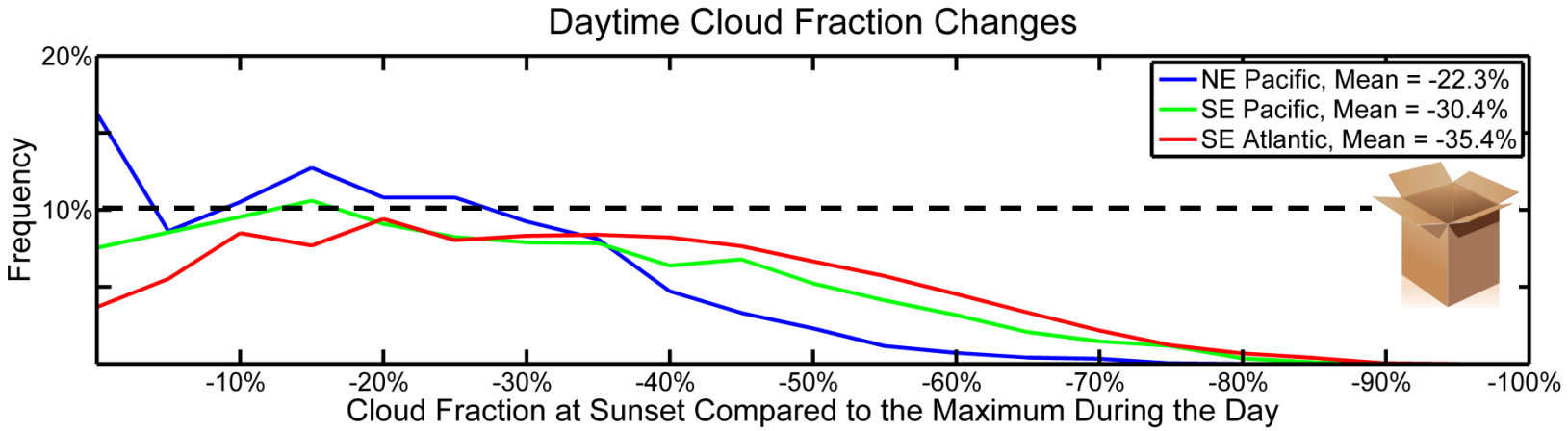
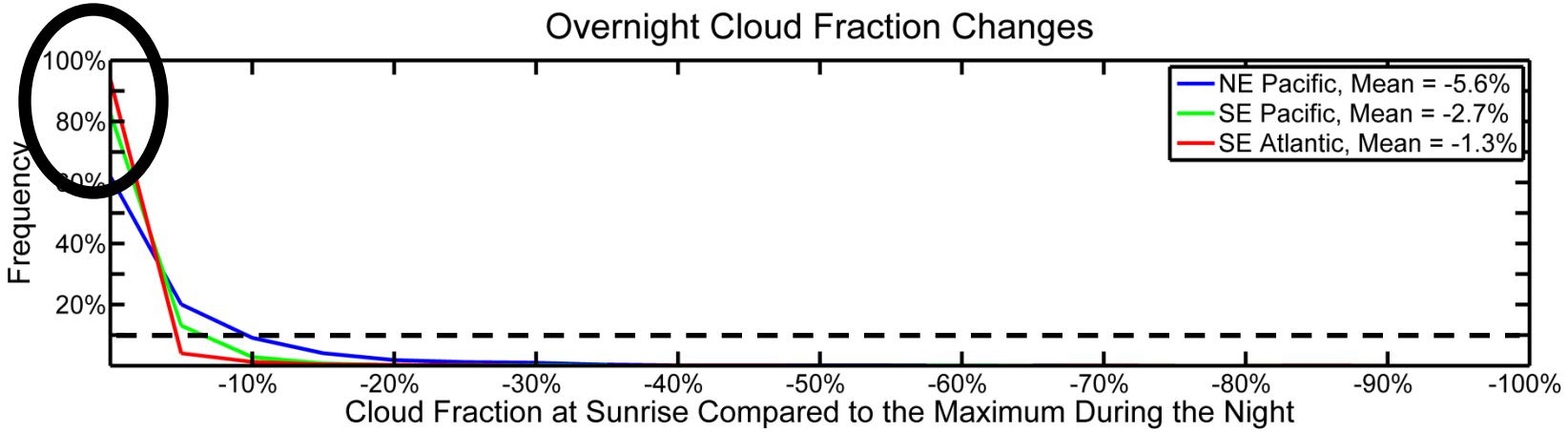
Any decrease in cloudiness overnight can be compared relative to the decreases that occur during the day…





Relative Magnitudes of Cloud Fraction Decreases – Day vs. Night

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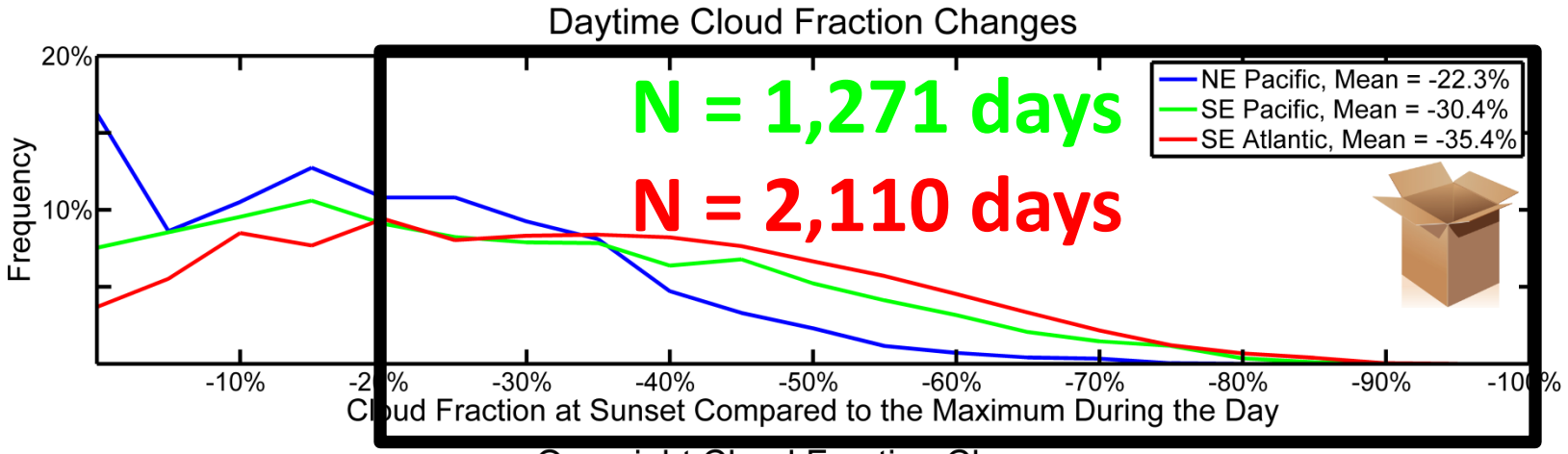
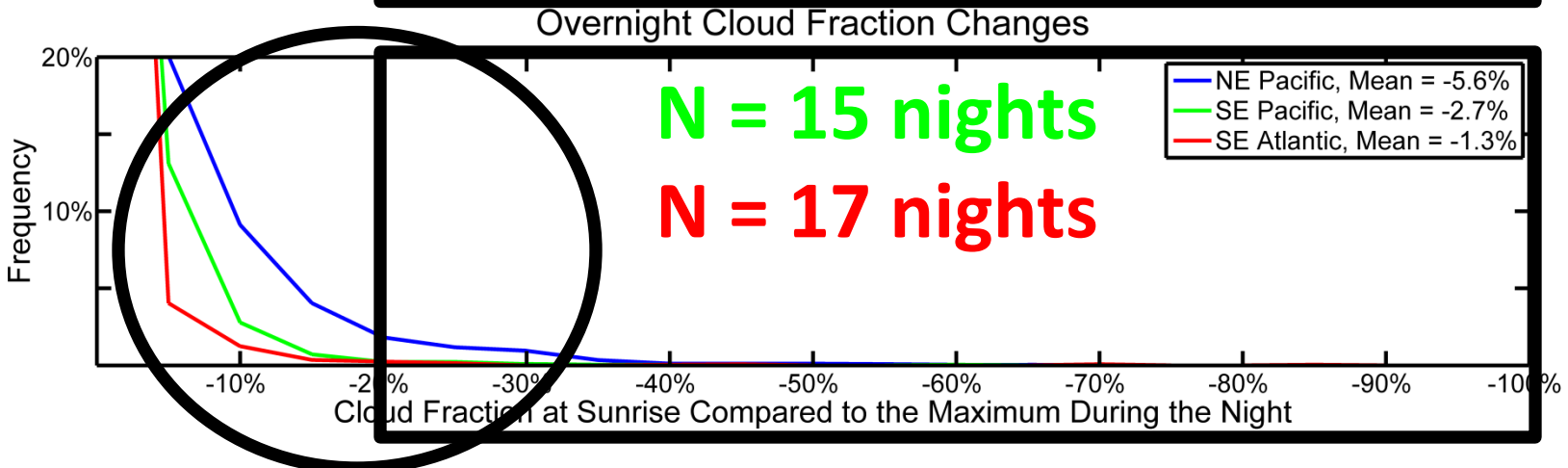
In the SE Pacific and SE Atlantic, the largest decreases observed overnight were the same magnitude as the normal decrease that occurs almost every day.





Examples of Decreasing Cloudiness Overnight

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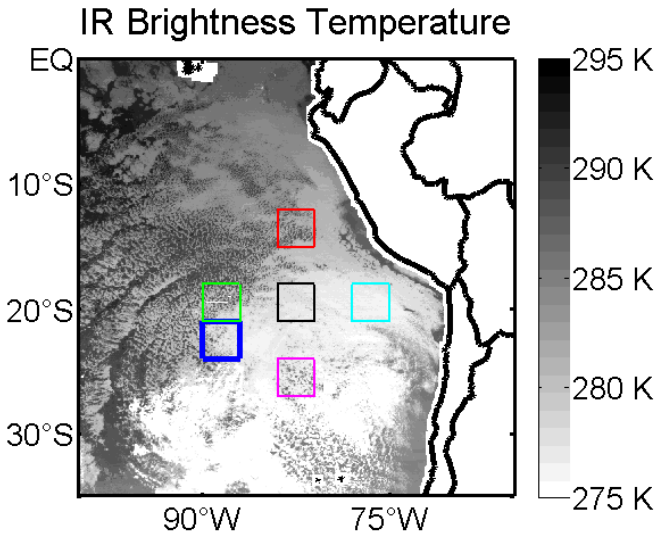
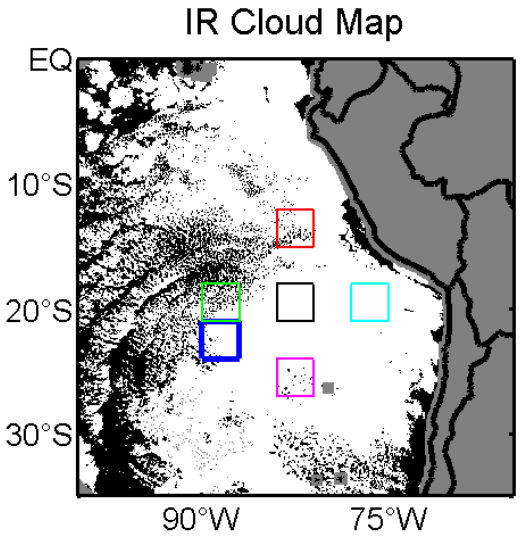
We can find cases of POCs forming in the domain…





SE Pacific

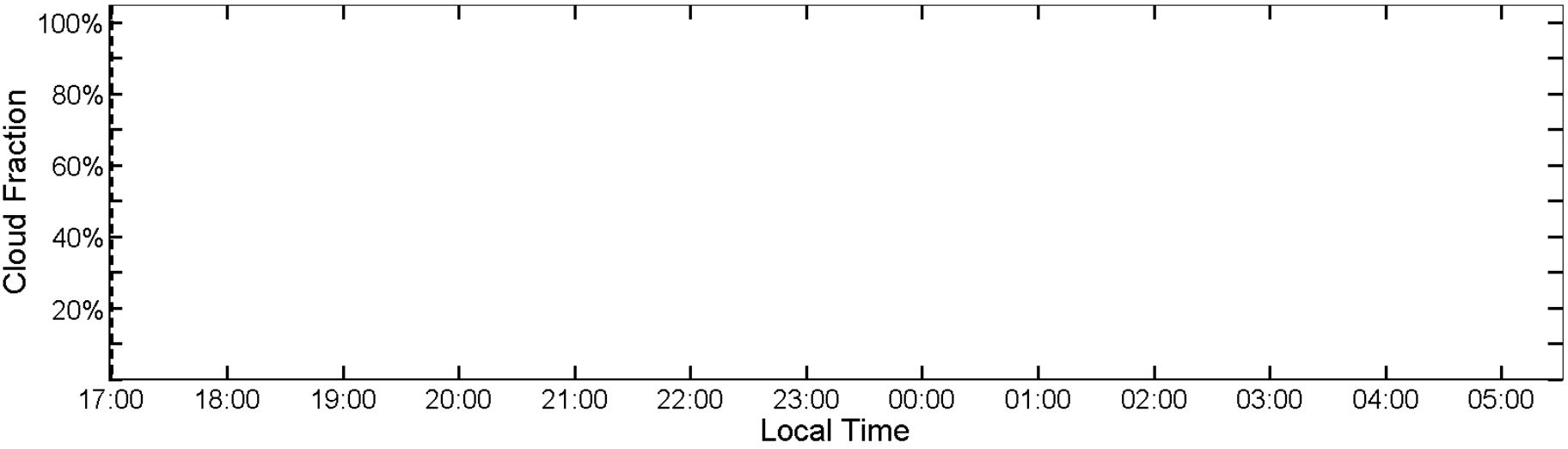
Start Day: 23-Aug 2003

Start Time: 23:00 UTC

End Day: 24-Aug 2003

End Time: 11:30 UTC

Cloud Fraction Change: -32%



Examples of Decreasing Cloudiness Overnight

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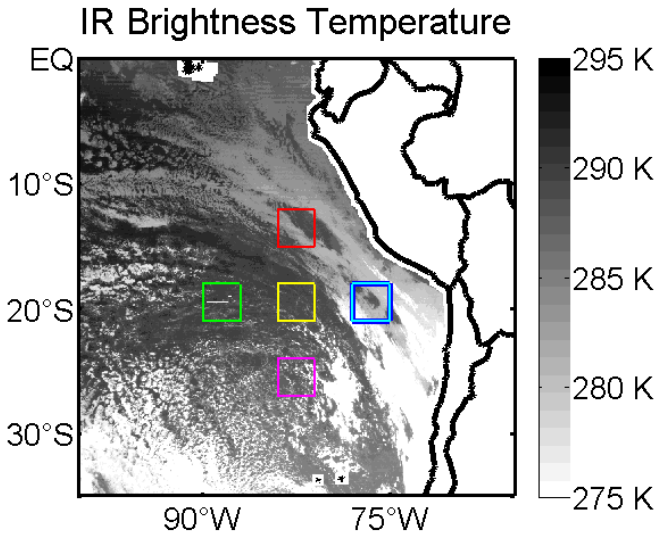
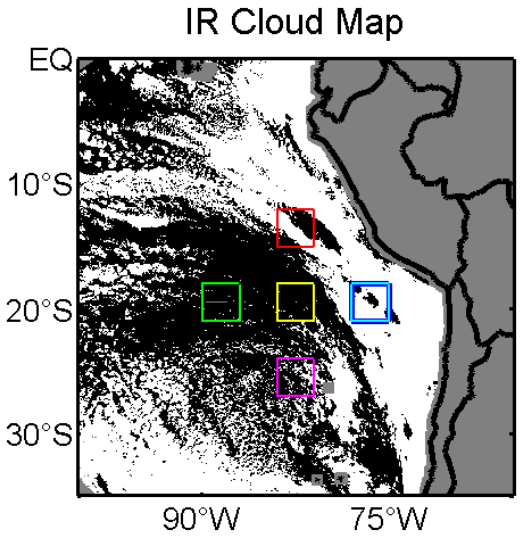
We can find examples of clearing that aren't related to POCs…





SE Pacific

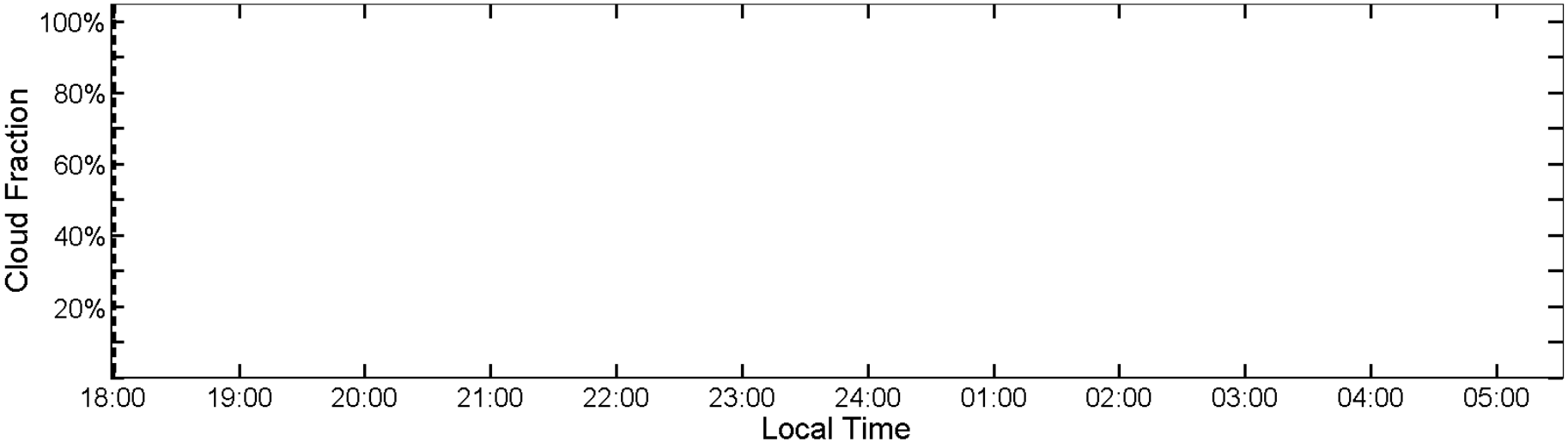
Start Day: 26-Jul 2004

Start Time: 23:00 UTC

End Day: 27-Jul 2004

End Time: 10:30 UTC

Cloud Fraction Change: -43%



Spatial Structure of the Frequency of Cloudiness Changes Overnight

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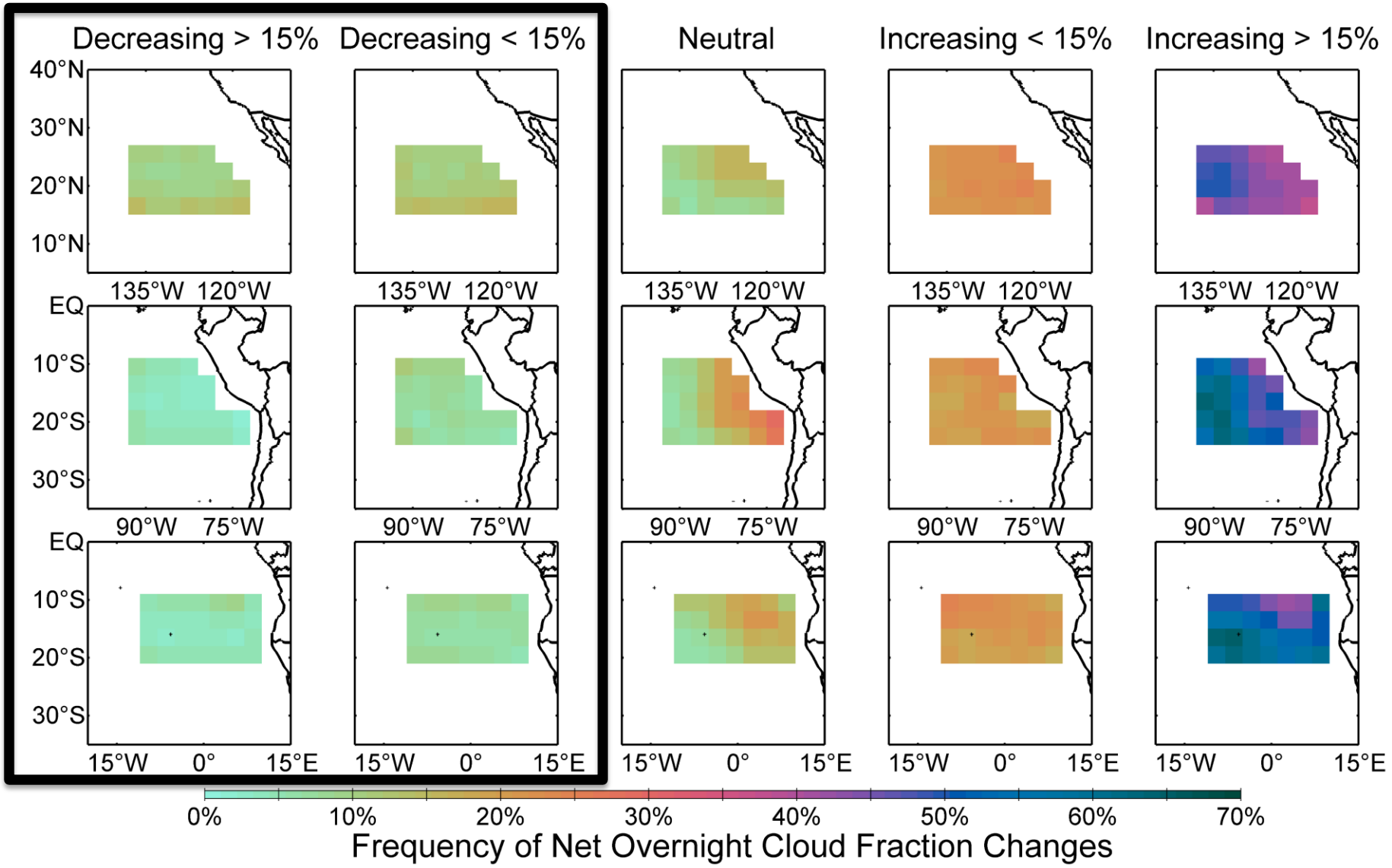

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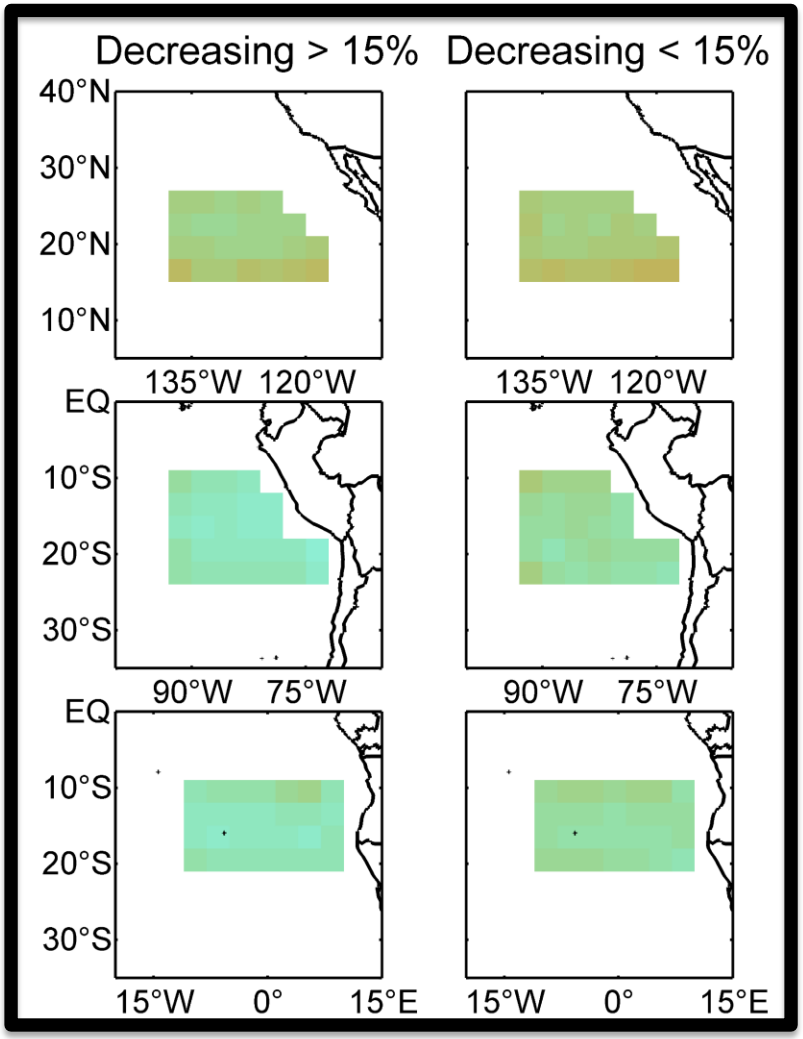


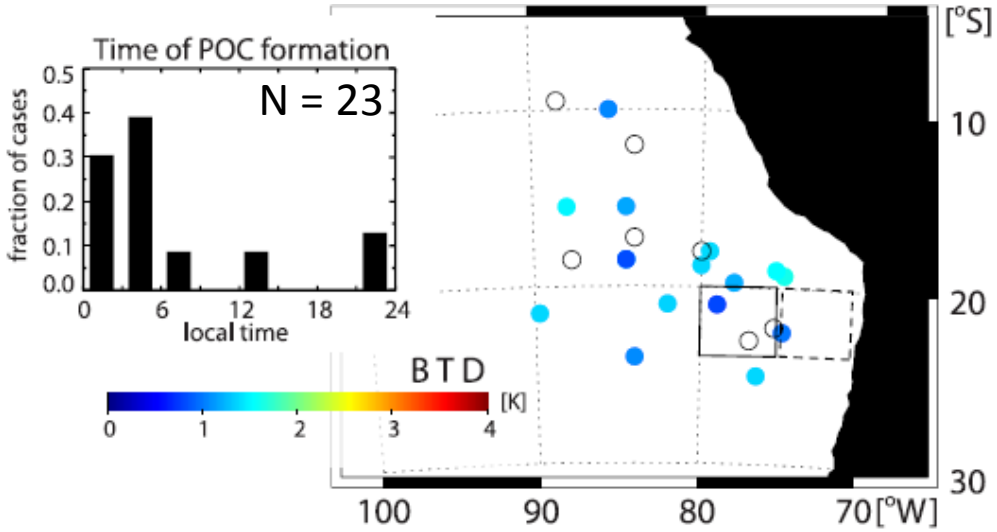
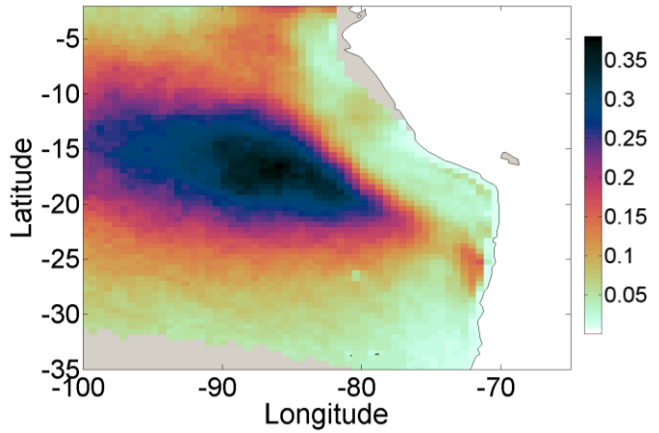


Figure 10a from Wood et al. (2008)

Drizzle Frequency at Night



Data from Margaret Frey (NCSU)

Environmental Characteristics When Cloud Fraction Decreases Overnight

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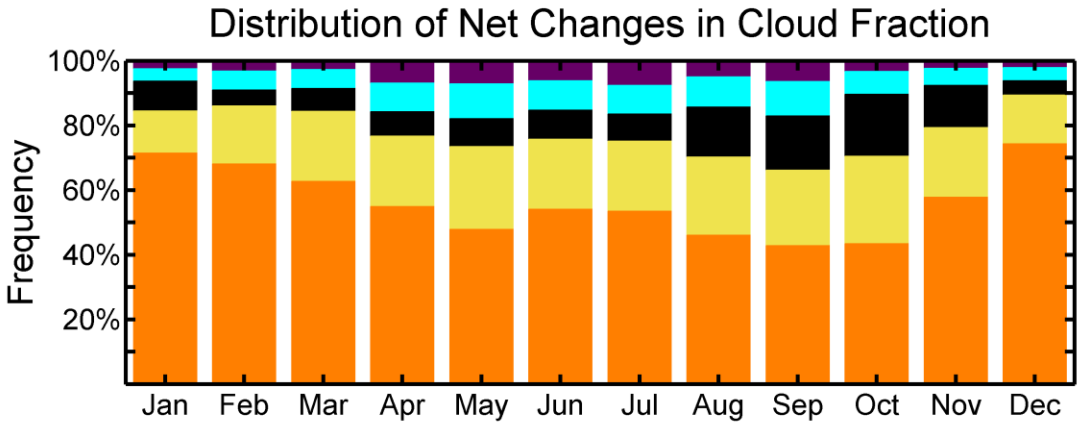

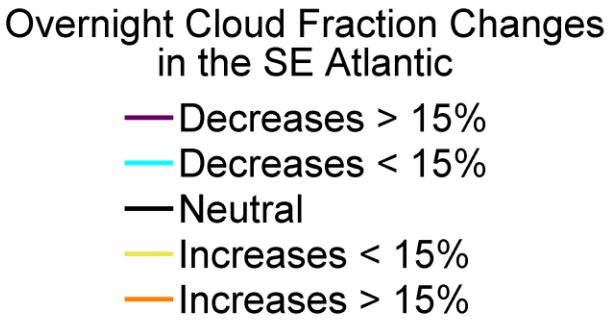

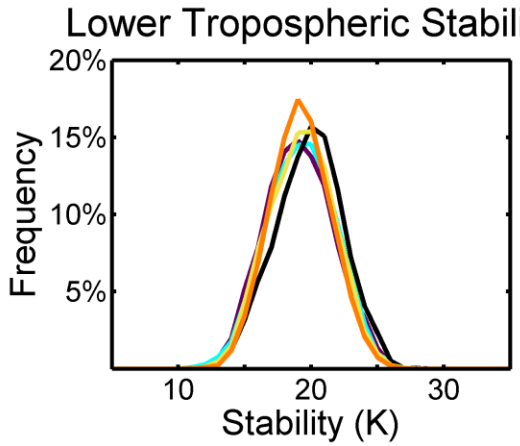

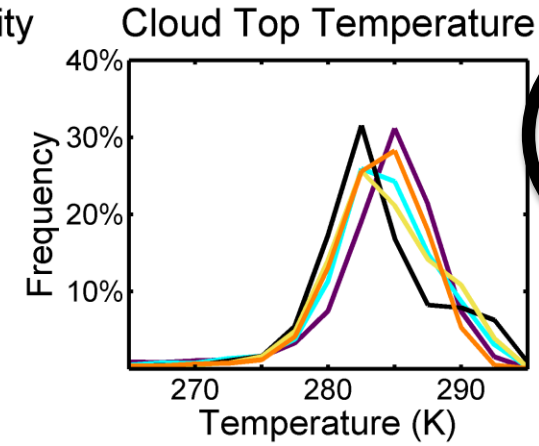

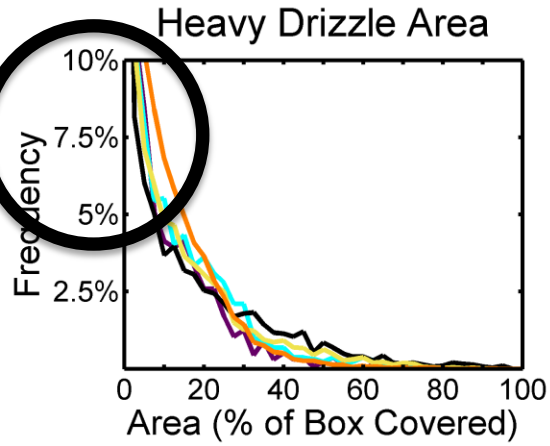

Stability Is Similar For All Scenarios

Warmer Cloud Tops When CF Changes Overnight

Drizzle Area Is Similar For All Scenarios

Cloud Fraction Sensitivity to Precipitation From Satellites

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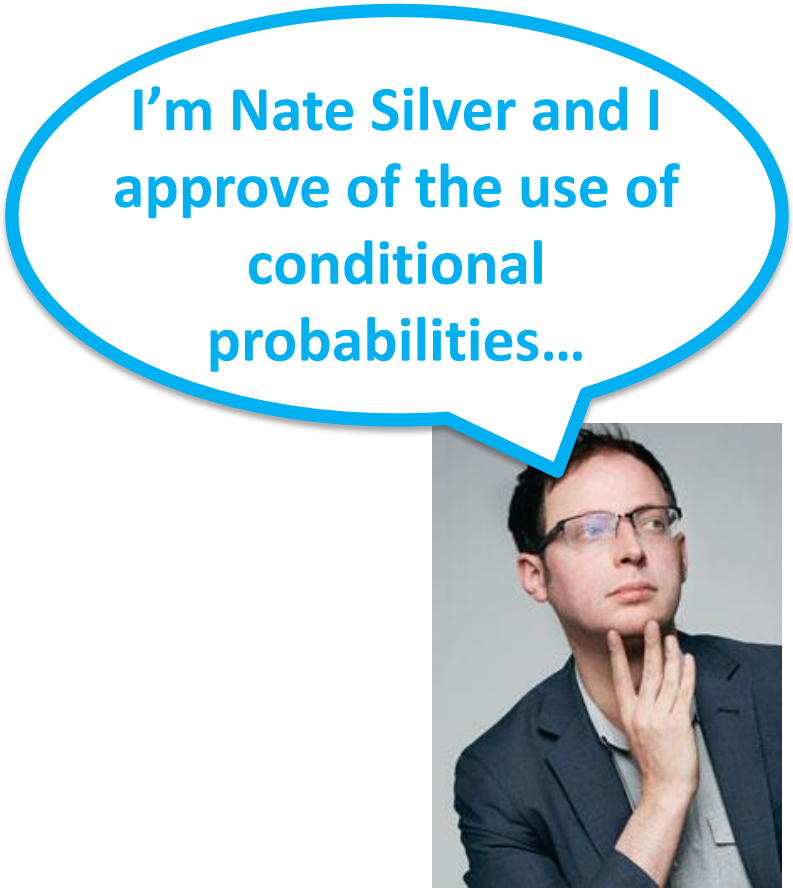
Basic Method

Use the 1:30 am MODIS overpass to characterize the area fraction of heavy drizzle in 3° x 3° boxes in the Sc regions, then use the IR cloud masks to track what happens to cloud fraction in the subsequent hours.



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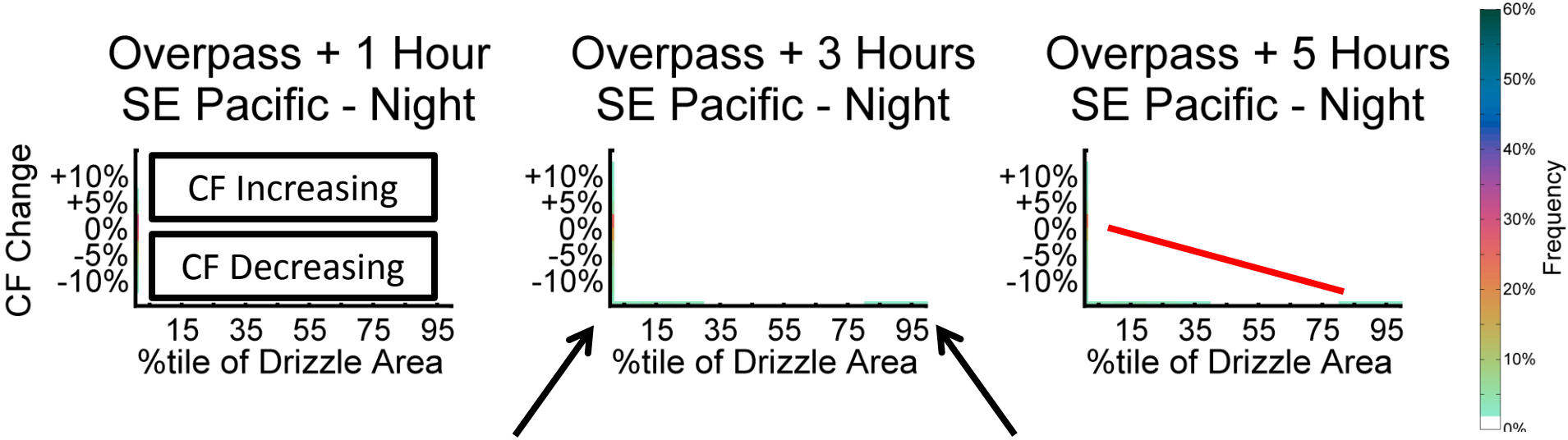

Least drizzle ever observed in that box

Most drizzle ever observed in that box

Cloud Fraction Sensitivity to Precipitation From Satellites

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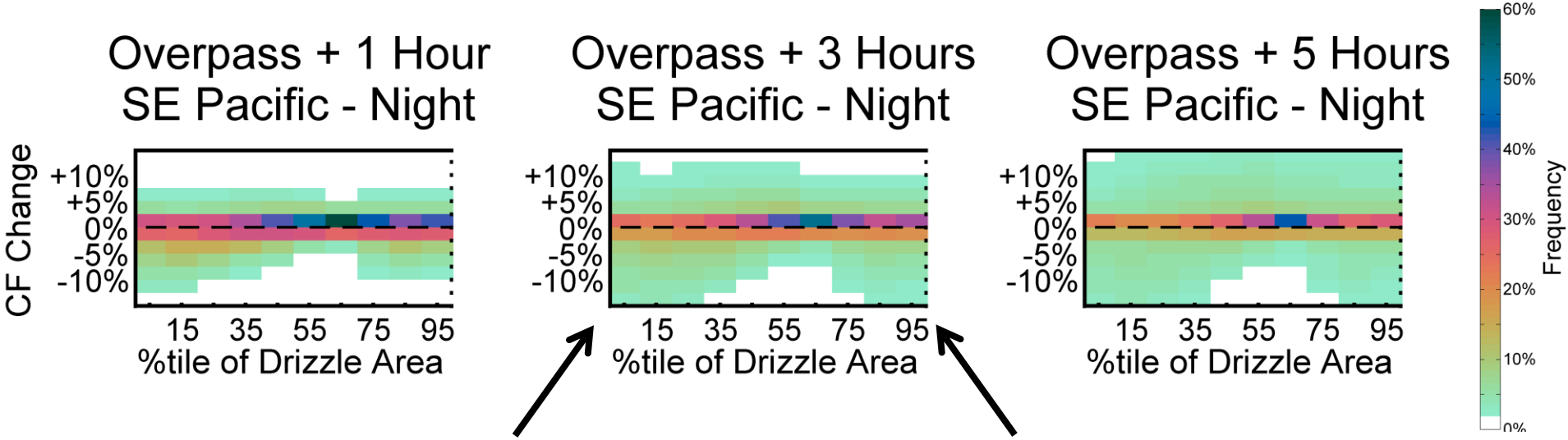


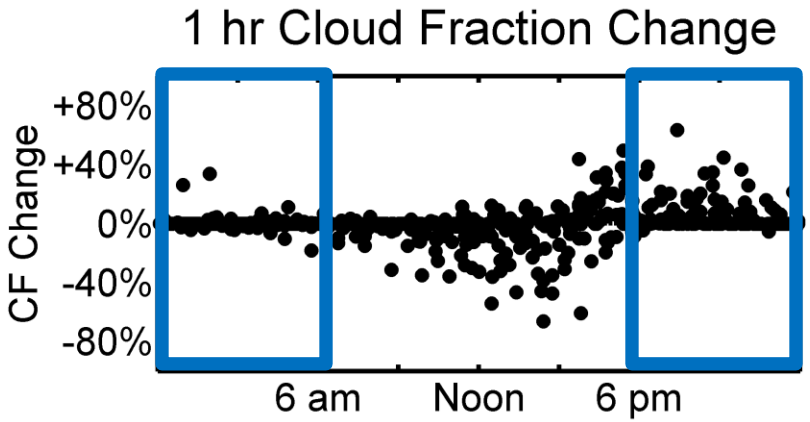
Least drizzle ever observed in that box

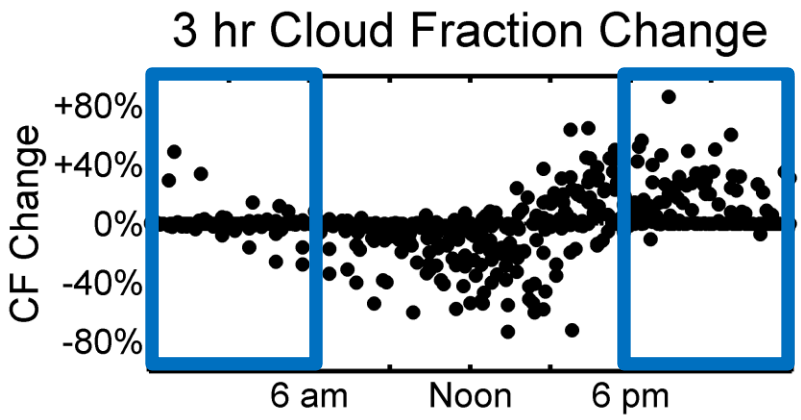
Most drizzle ever observed in that box

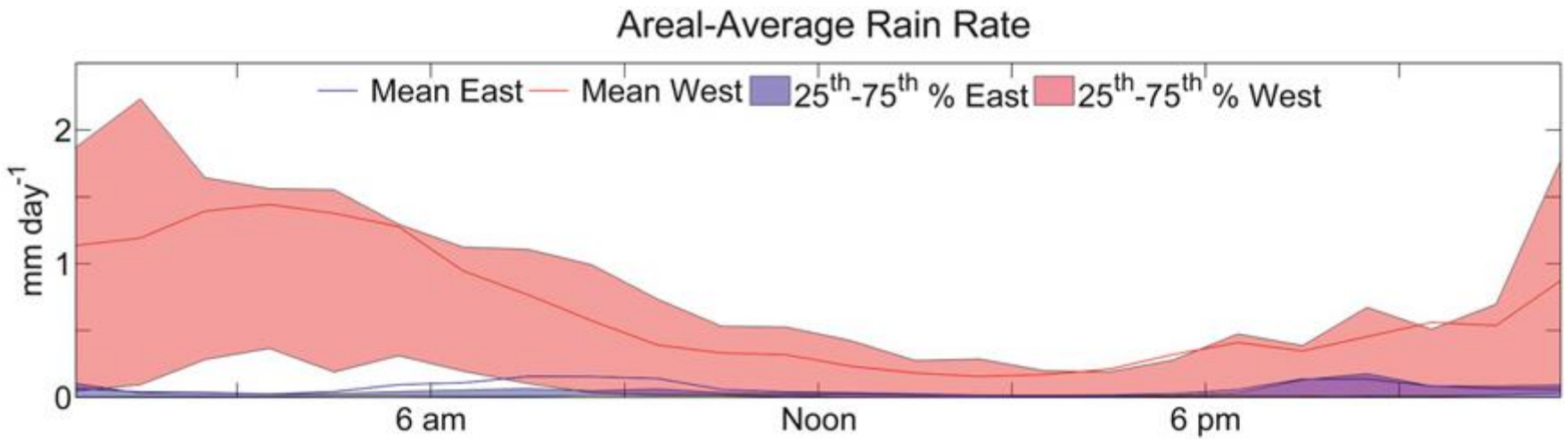
Cloud Fraction Sensitivity to Precipitation during VOCALS-REx

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

I used the merged-IR cloud masks to calculate cloud fraction within a 1° x 1° box centered on the ship…







Cloud Fraction Sensitivity to Precipitation during VOCALS-REx

Pacific Northwest
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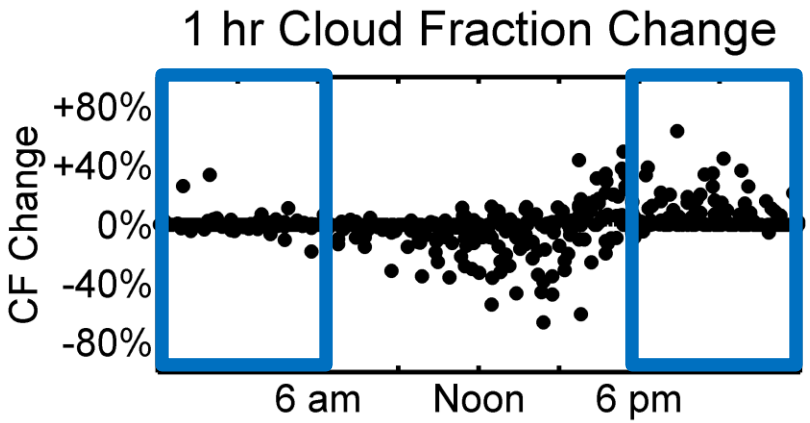

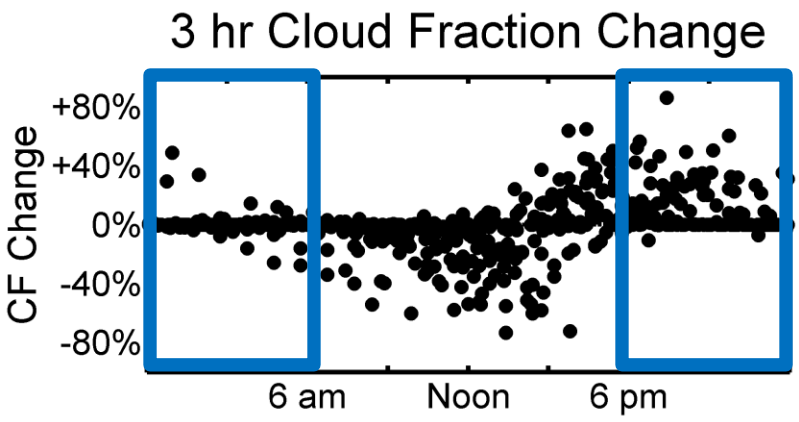

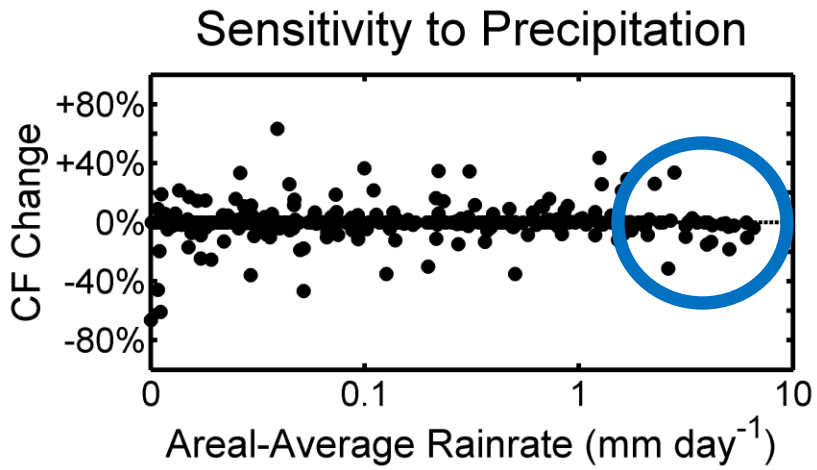

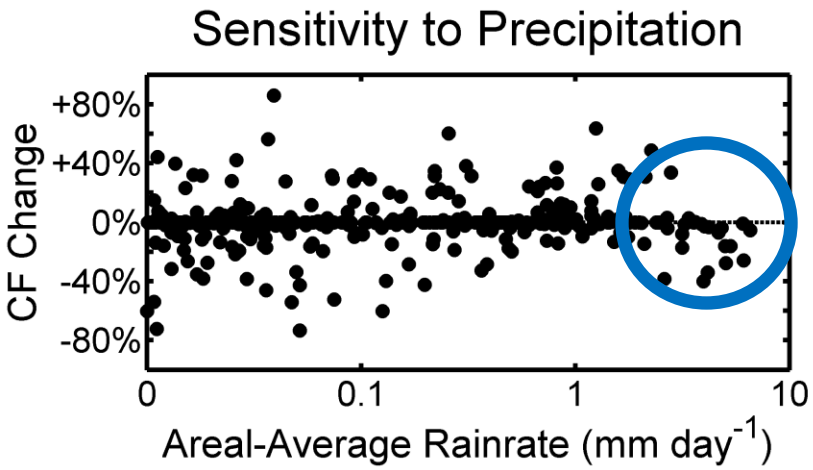

Cloud Fraction Sensitivity to Precipitation during VOCALS-REx

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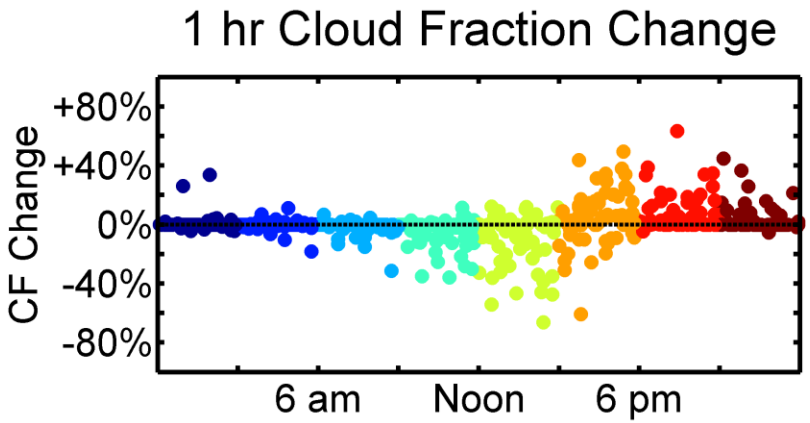
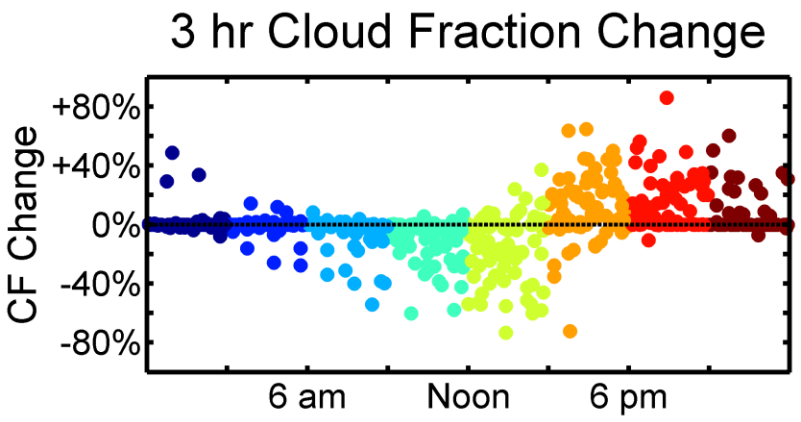
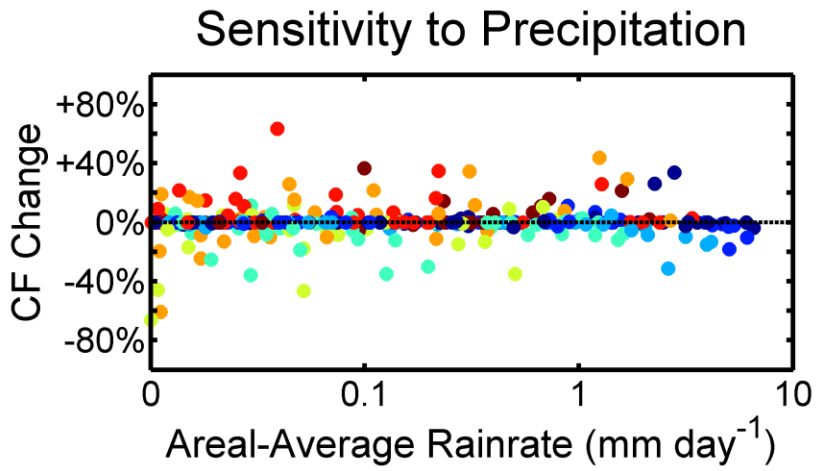
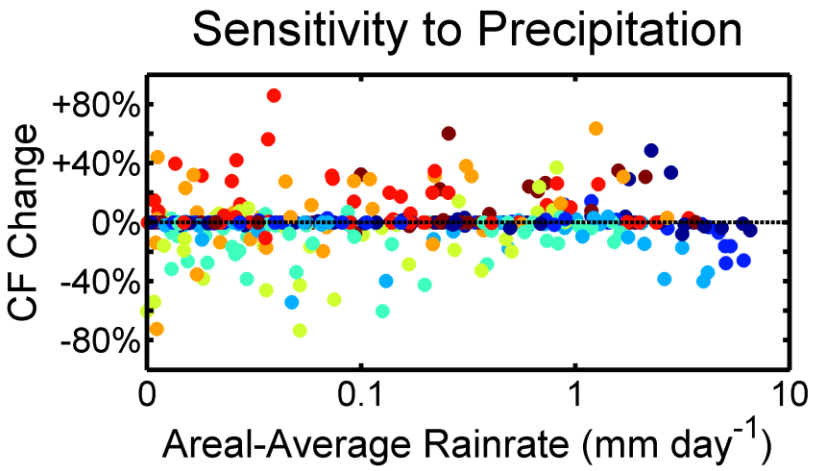
I used the merged-IR cloud masks to calculate cloud fraction within a 1° x 1° box centered on the ship…









Conclusions – Corroborative

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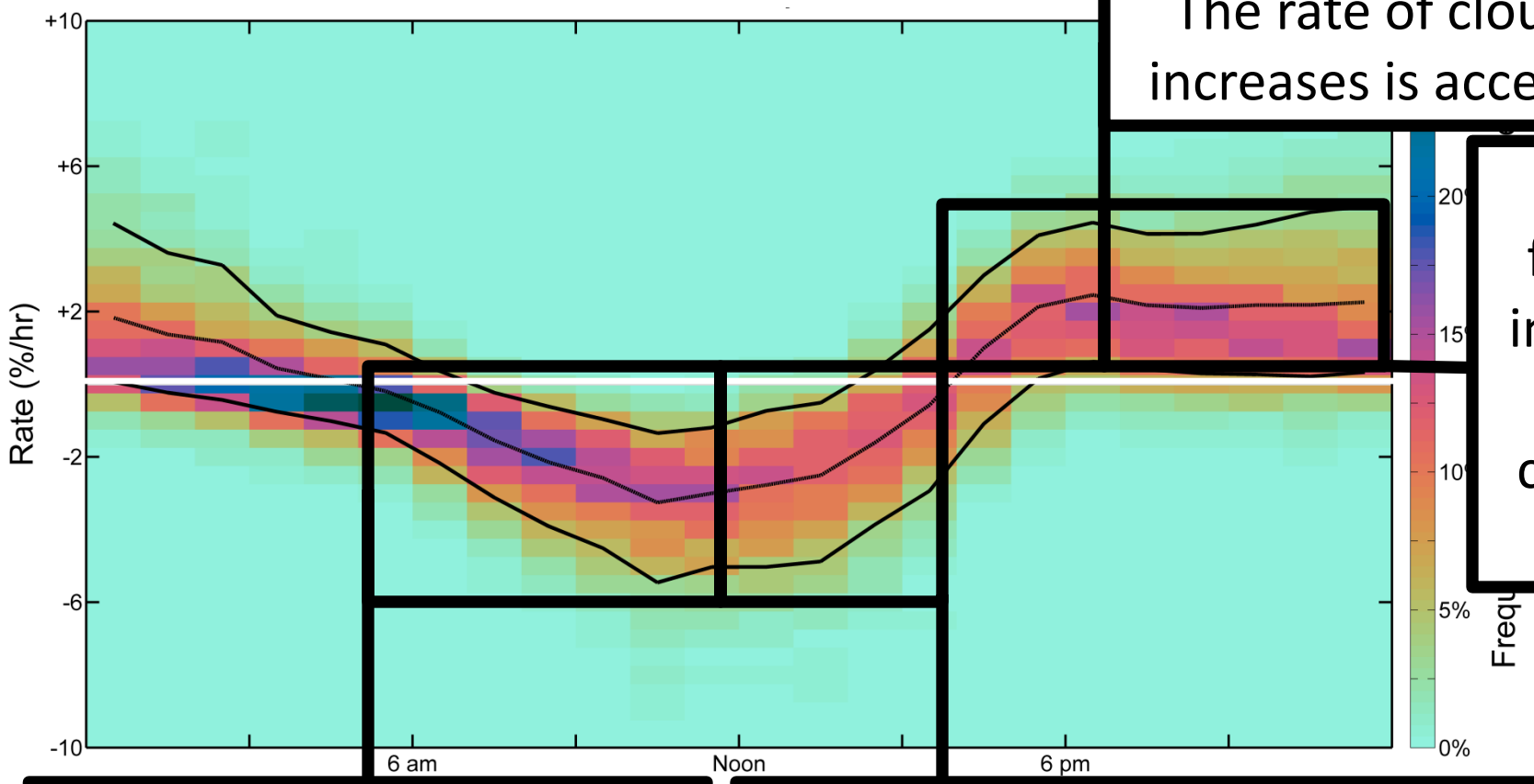
1) The rate of cloud breakup and reformation is very closely related to shortwave radiative flux.



The rate of cloudiness increases is accelerating

Cloud fraction increases at a constant rate

Rate of cloud breakup accelerates

Cloud fractions are still decreasing but at a slower rate

Conclusions – Corroborative

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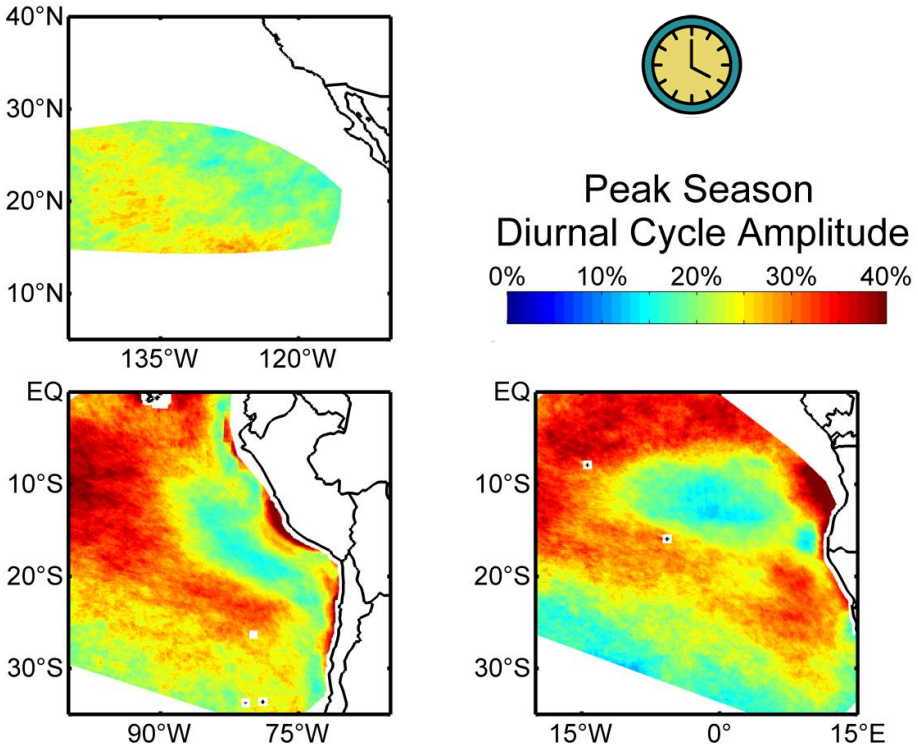
2) The largest diurnal cycles and earliest time of cloud break up occur on the edges of the cloud field where cloud fractions are in general lower. This could be evidence for the positive feedback through which low cloud fraction regions create conditions more favorable for cloud breakup.



Conclusions – New Results

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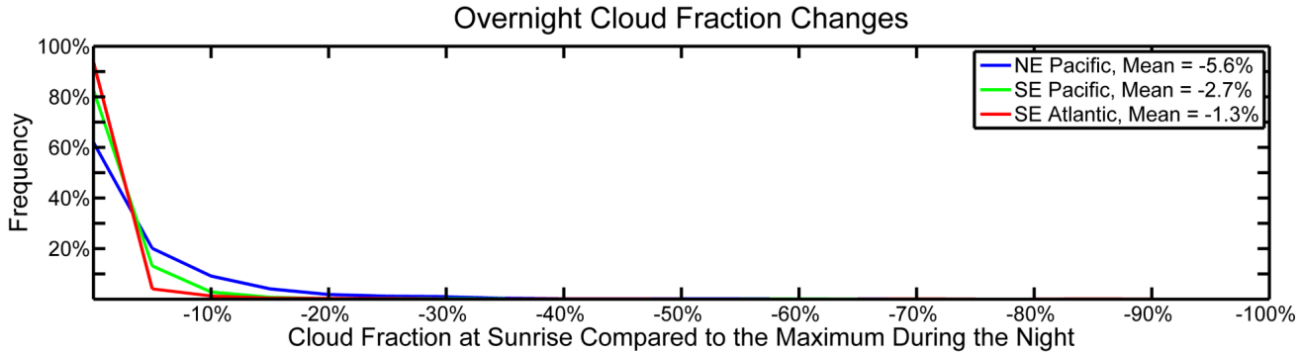
3) In the SE Pacific and SE Atlantic, a 3° x 3° region that saw cloudiness increase above 90% at any point during the night has only a 1 in 65 chance of having a cloud fraction lower than 60% at sunrise. Large decreases in cloudiness overnight, such as those that would result from POC formation, occur very rarely (< 1.5% of the time).

"The *frequency and climatic importance of POCs* remains poorly characterized." – Mechoso et al. (2014)



Conclusions – New Results

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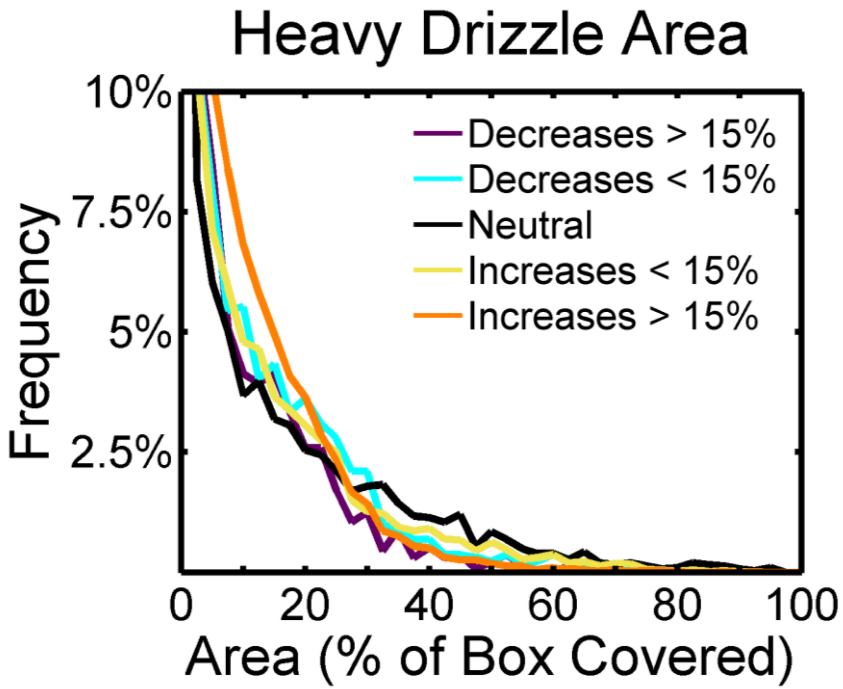
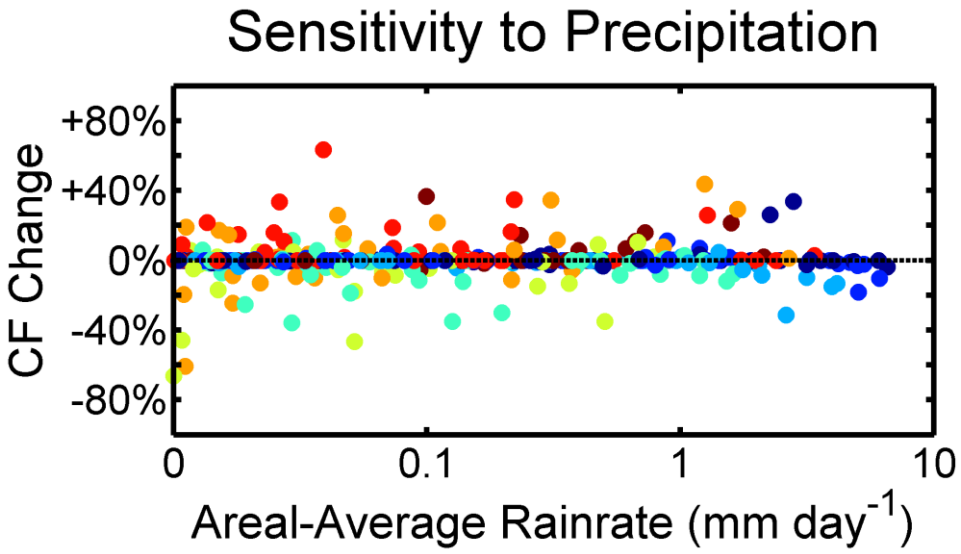
4) Overnight, cloud fraction changes at 100-300 km spatial scales and < 5 hour temporal scales show minimal sensitivity to either precipitation area or intensity. Drizzle is neither a necessary nor sufficient condition for reducing cloud fraction overnight.





Implications

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- Addressing the processes that lead to variability on diurnal and seasonal time scales should go a long way toward improving overall simulation of cloud fraction variability.

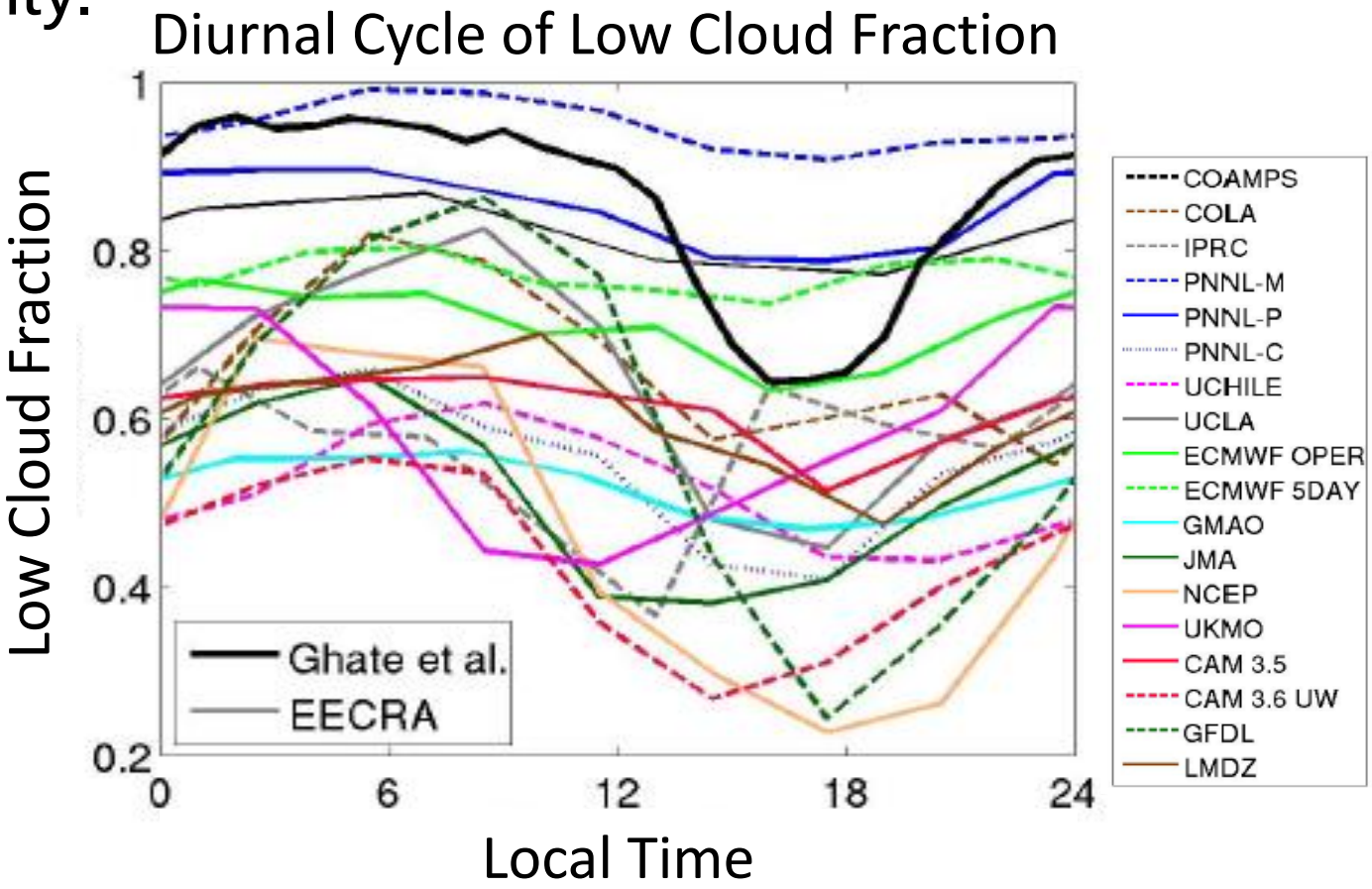

Fig. 11b from Wyant et al. (2010)

Implications

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- Addressing the processes that lead to variability on diurnal and seasonal time scales should go a long way toward improving overall simulation of cloud fraction variability.

- Modeling studies of specific processes which can influence cloud fraction should consider comparing the magnitude of the forced variability against the amplitude of the mean diurnal cycle.

Conclusions

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1) The rate of cloud breakup and reformation is very closely related to shortwave radiative flux. (Corroborative)

2) The largest diurnal cycles and earliest time of cloud break up occur on the edges of the cloud field where cloud fractions are in general lower. This could be evidence for the positive feedback through which low cloud fraction regions create conditions more favorable for cloud breakup. (Corroborative)

3) In the SE Pacific and SE Atlantic, a 3° x 3° region that saw cloudiness increase above 90% at any point during the night has only a 1 in 65 chance of having a cloud fraction lower than 60% at sunrise. Large decreases in cloudiness overnight, such as those that would result from POC formation, occur very rarely (< 1.5% of the time). (New Result)

4) Overnight, cloud fraction changes at 100-300 km spatial scales and < 5 hour temporal scales show minimal sensitivity to either precipitation area or intensity. Drizzle is neither a necessary nor sufficient condition for reducing cloud fraction overnight. (New Result)