

# Equilibrium large eddy simulations of boundary layer clouds: motivation plus an example

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# Motivation

- Six hour LES intercomparisons of boundary layer evolution (GCSS) show continually improving skill but ...
- Time scales for a well-mixed cloud layer are much longer (Schubert et al., 1979, Zhang et al., 2005)
  - $\tau_h$  = adjustment time for boundary layer height  $\sim$  1 week
  - $\tau_b$  = adjustment time for cloud base height  $\sim$  1 day
- Longer runs, (possibly) independent of initial conditions, would be useful for:

## Motivation, continued ...

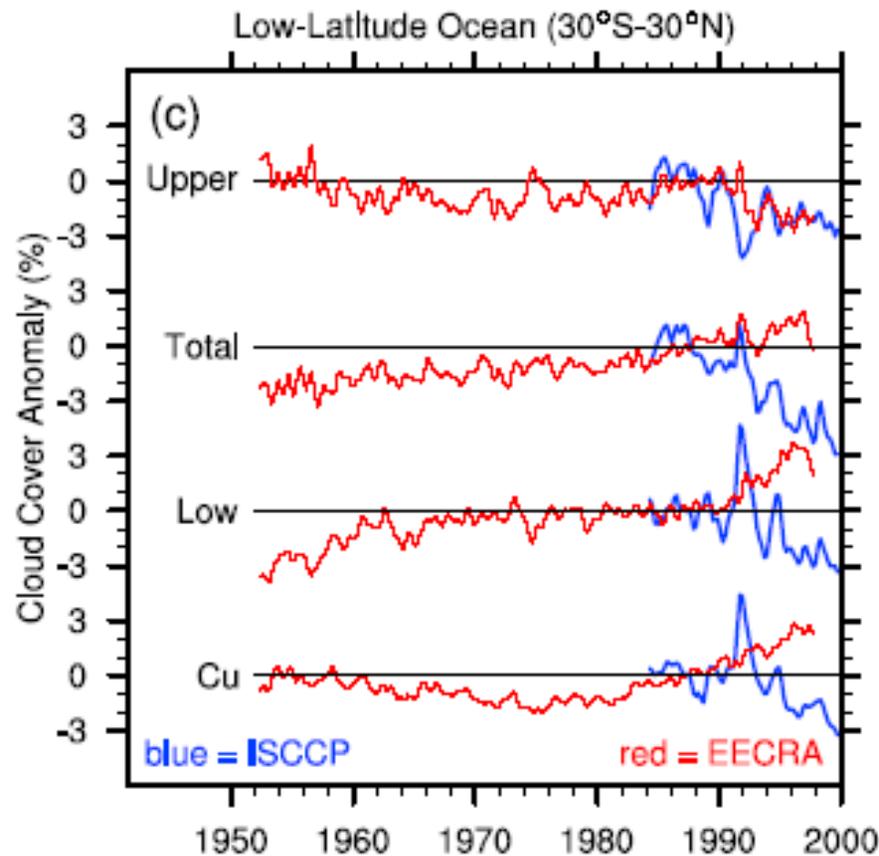
- Tests of LES advection and subgrid scale turbulence parameterizations at a range of horizontal and vertical resolutions
- Establishing boundary layer cloud response to large scale perturbations
- Characterizing boundary layer PDFs (Lewis et al., JGR 2004)

### This talk looks at:

- A motivational case: observed cloud-trends in the tropical Pacific: 20 year JJA climatology
- LES equilibria for a climatology plus perturbation: 97/98 El Nino using the CSU SAM (thanks to Marat Khairoutdinov)

# Cloud trends ...

- Satellites (ISCCP, ERBS, CERES) and surface observers (e.g. Norris, 2005) agree that zonal mean global mid/upper level cloud amounts are decreasing, but they disagree on low level cloud trends



Norris, JGR, 2005

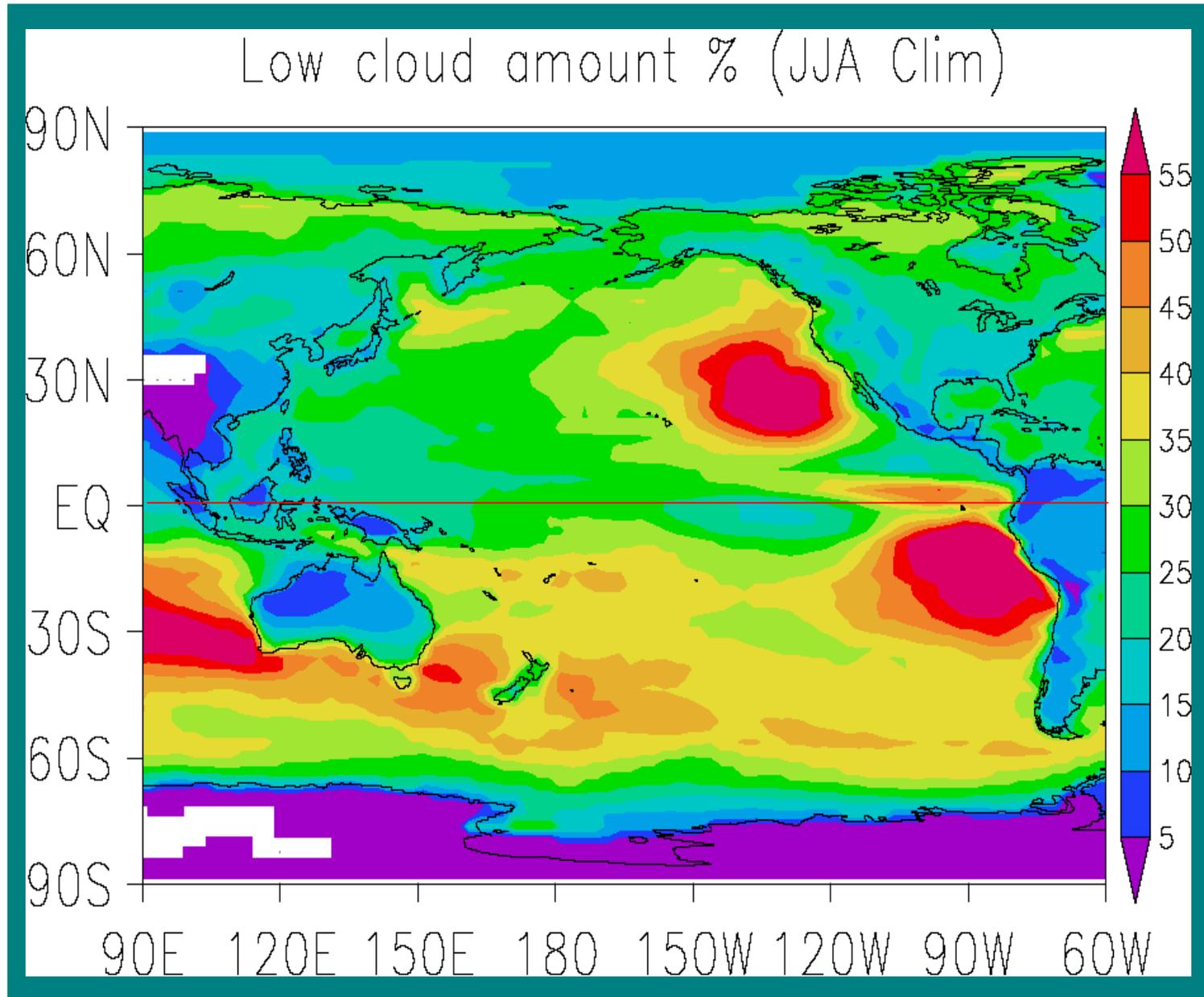
# Cloud trends ...

- Norris, 1998, Bajuk and Leovy, 1998 etc. have shown strong correlations between cumulus frequency and mean surface convergence/divergence over tropical/Indian oceans
- Chen et al., 2002 show that CERES long/sw measurements are consistent with strengthening ascending/descending branches of Hadley circulation.
- Mitas and Clement, 2005, find the signal in the NCEP1 and ERA-40 reanalyses, but nothing in the NCEP2 and rawinsonde data. For CAM forced by SSTs, the circulation strengthens, but is weaker than reanalysis

## Our approach: look at NCEP1 in JJA tropical Pacific

- Use ISCCP D2 daytime and NCEP1 for JJA, tropical Pacific, July 83-Sep 2001
- Composite over two 4 year periods. Look at NCEP fields in the context of the ISCCP cloud trends and a boundary layer LES.

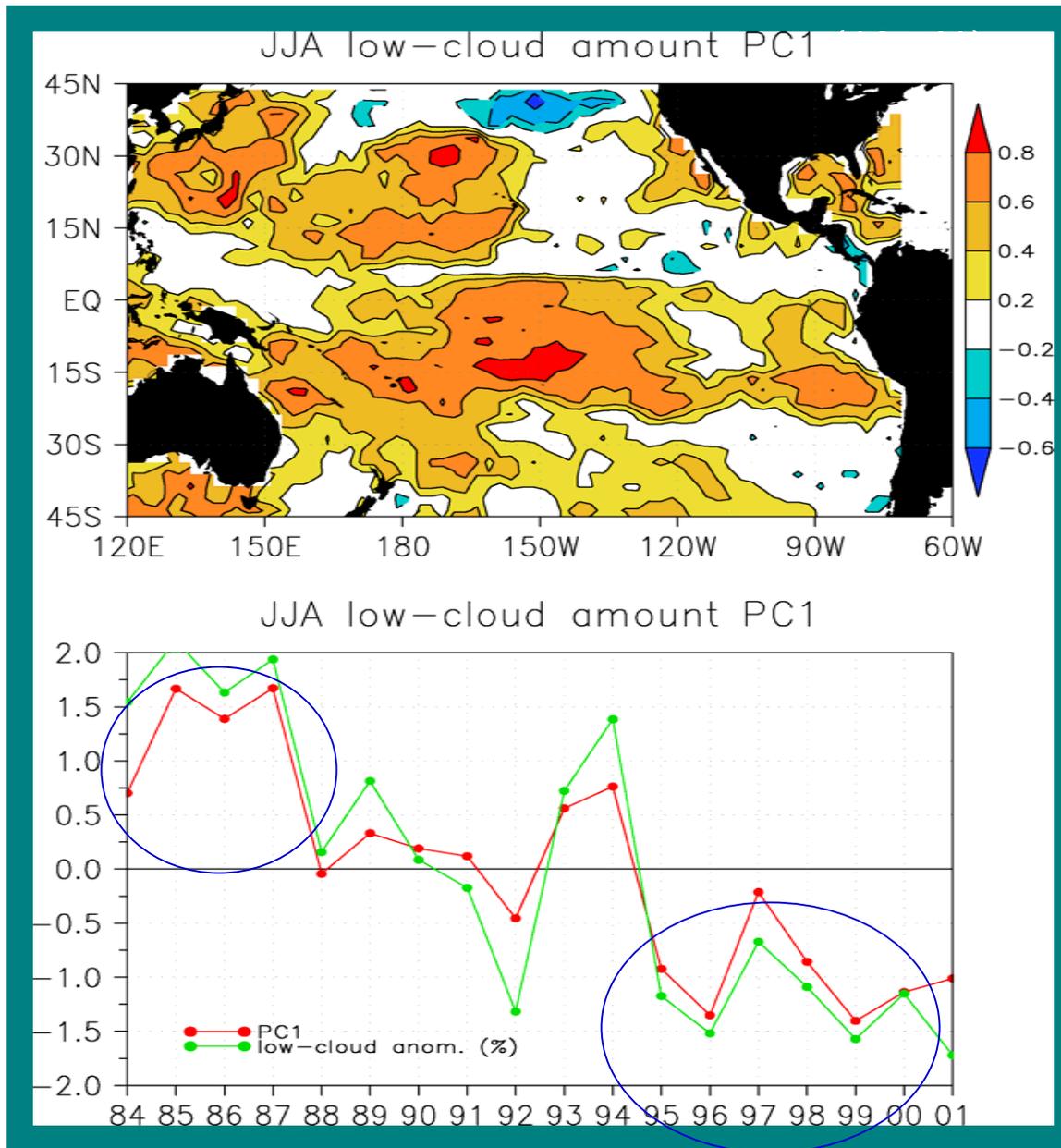
# ISCCP D2 daytime low cloud amount JJA



# Datasets

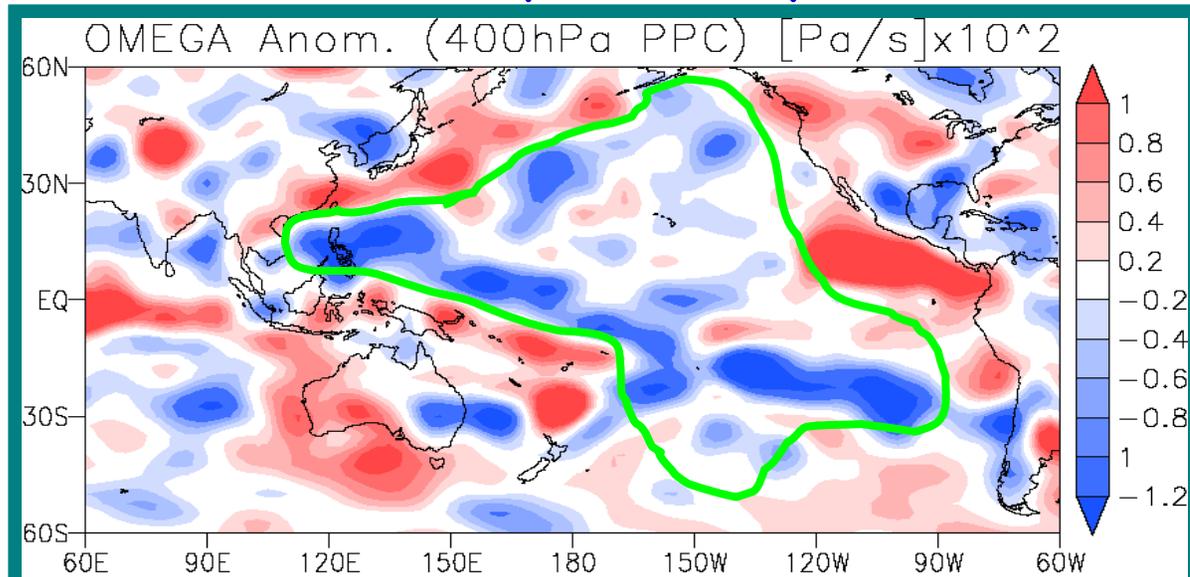
- ISCCP D2 Jul.1983-Sep.2001 daytime low cloud amount
- NCEP1 (NCEP/NCAR) and ERA-40 reanalyses
  - JJA, 120E-70W, 45S-45N
  - Velocity potential at 925 hPa,  $\chi = \nabla^{-2} D$ ,  $D = \nabla \cdot \mathbf{V}$
  - Divergent winds at 925 hPa  $\mathbf{V}_\chi = -\nabla \chi$
  - Vertical pressure velocity anomaly at 400 hPa
  - Geopotential height anomaly at 925 hPa

# PC1 for low-cloud anomaly from ISCCP-D2, JJA

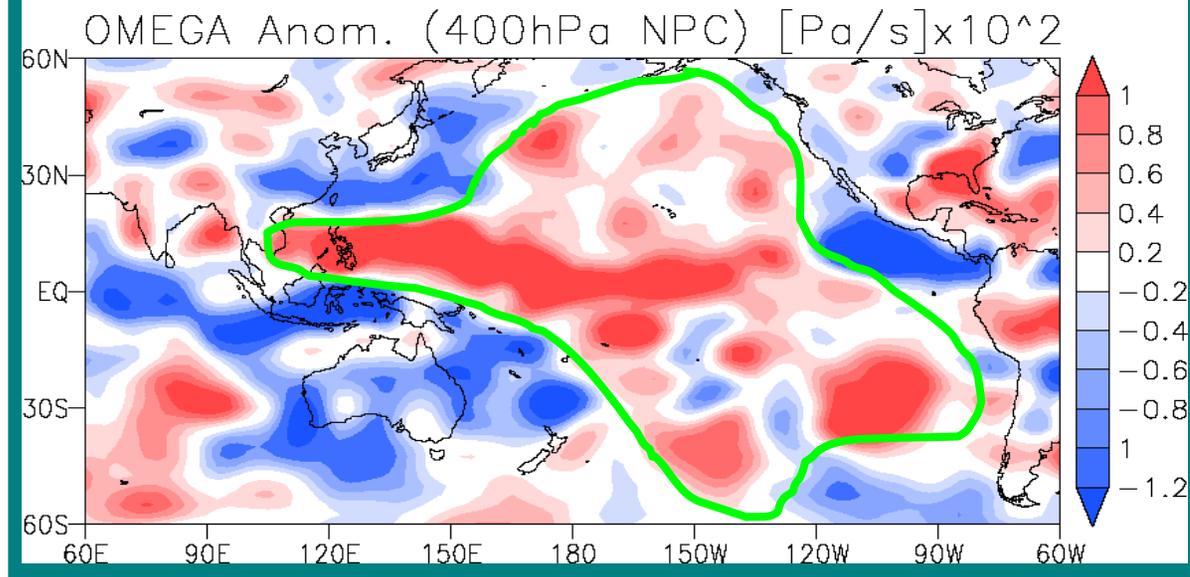


# Composites of 400hPa Vertical Pressure Velocity Anomaly

**Pos. cloudiness  
years: 84,85,86,87**

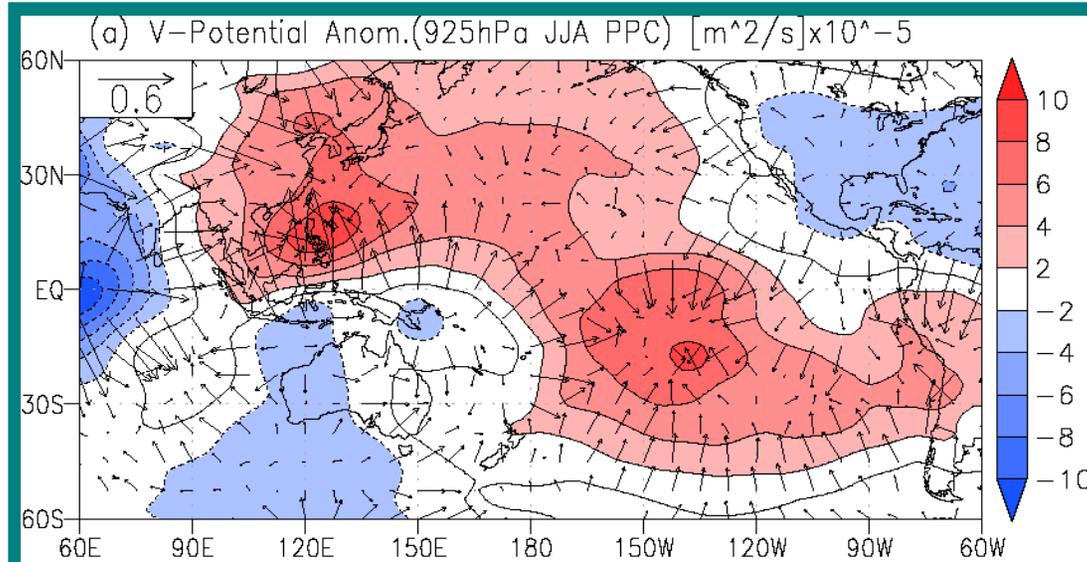


**Neg. cloudiness  
years: 96,98,99,00**

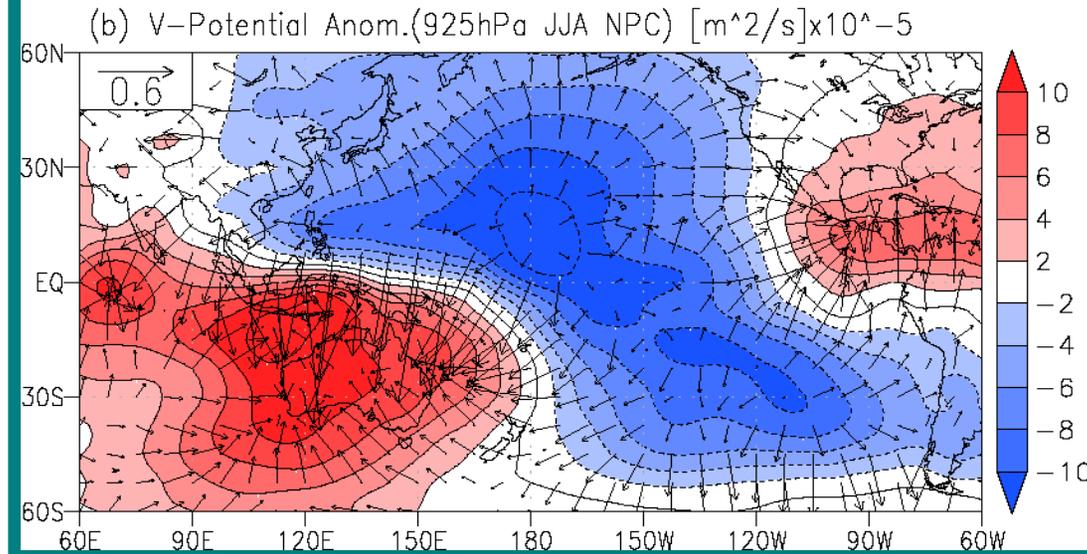


# Composites of 925hPa Velocity Potential and Divergent Wind Anomaly

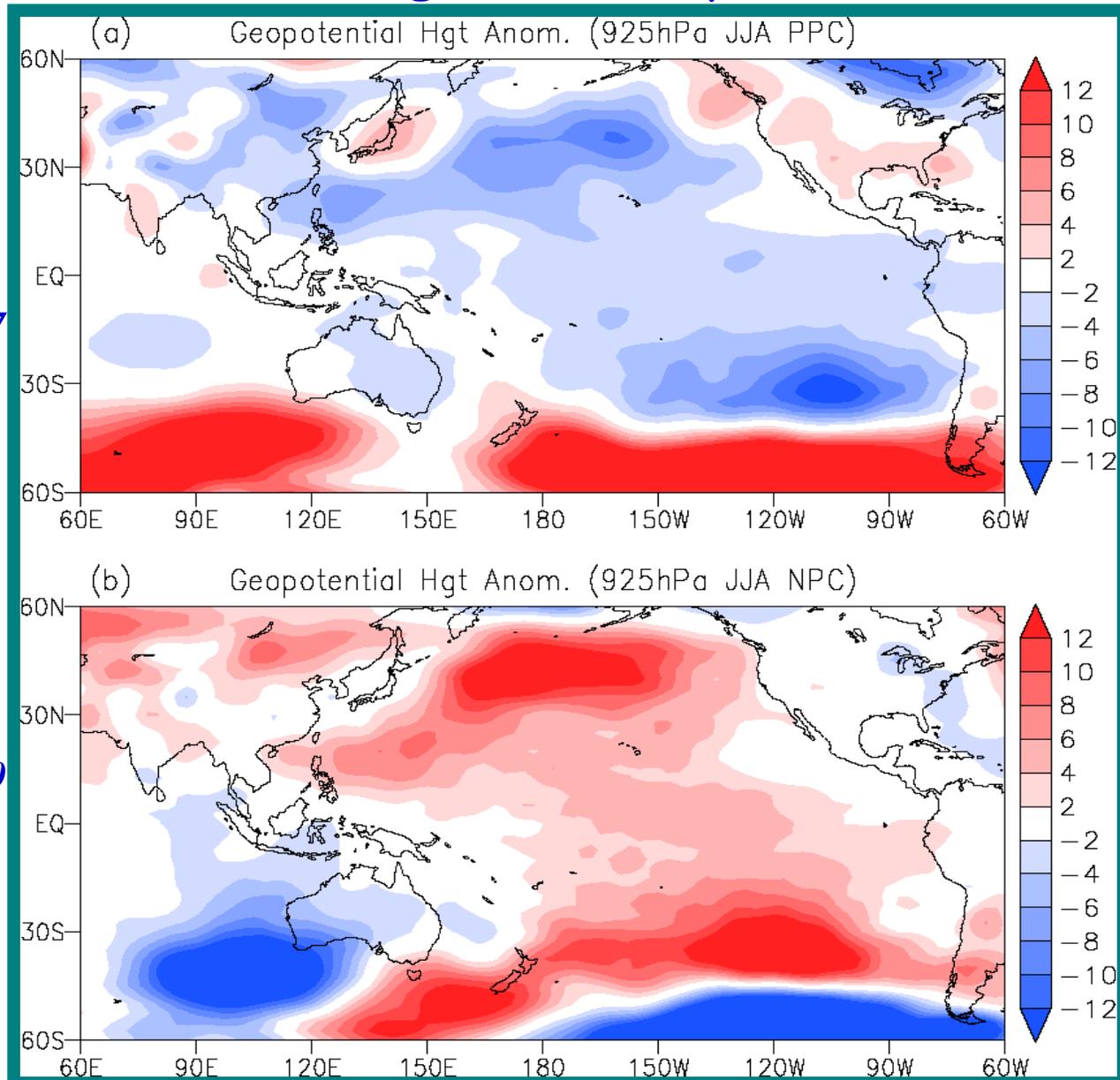
**Pos. cloudiness  
years: 84,85,86,87**



**Neg. cloudiness  
years: 96,98,99,00**



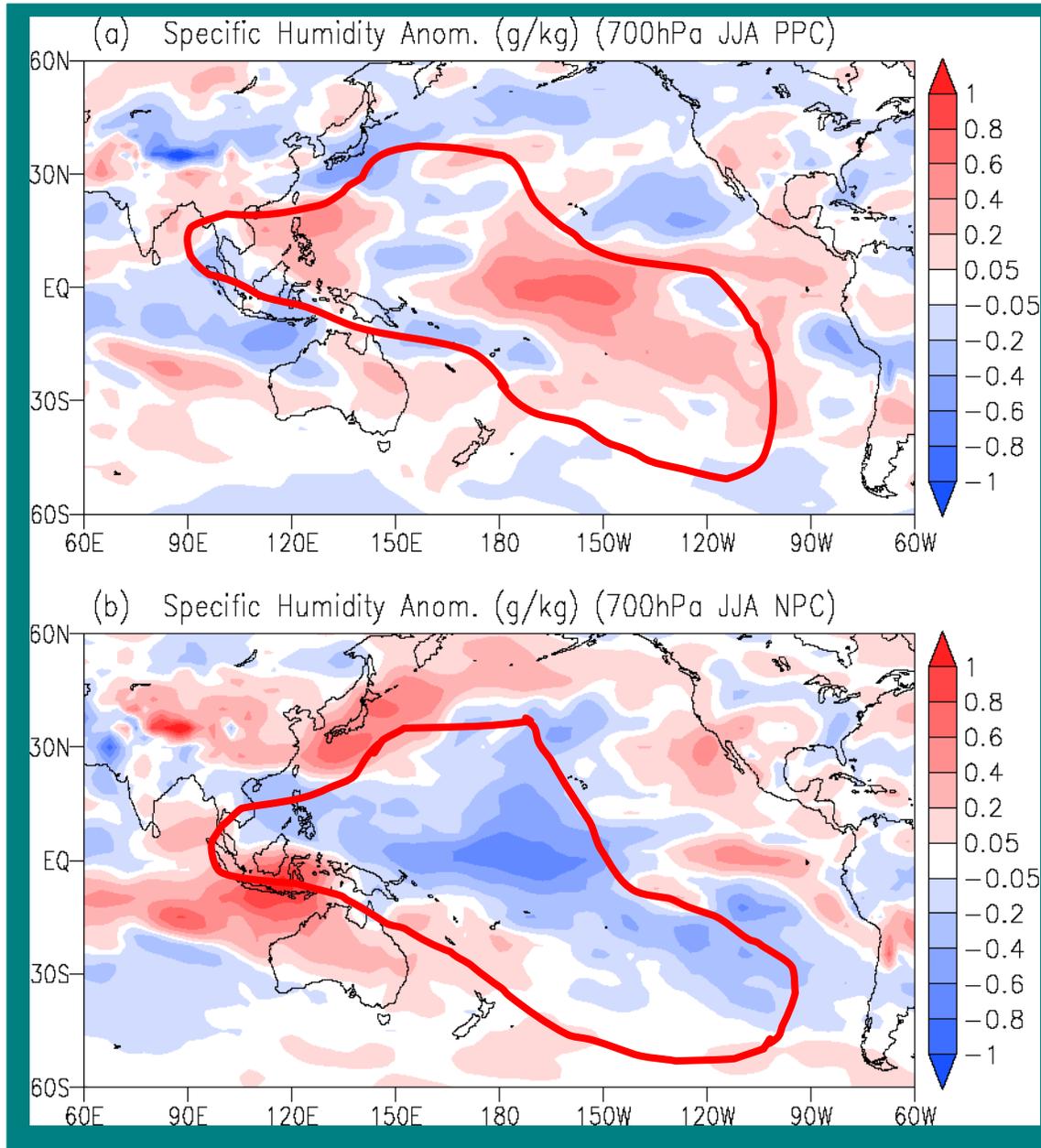
# Composites of 925 hPa Geopotential Height Anomaly



**Pos. cloudiness**  
years: 84,85,86,87

**Neg. cloudiness**  
years: 96,98,99,00

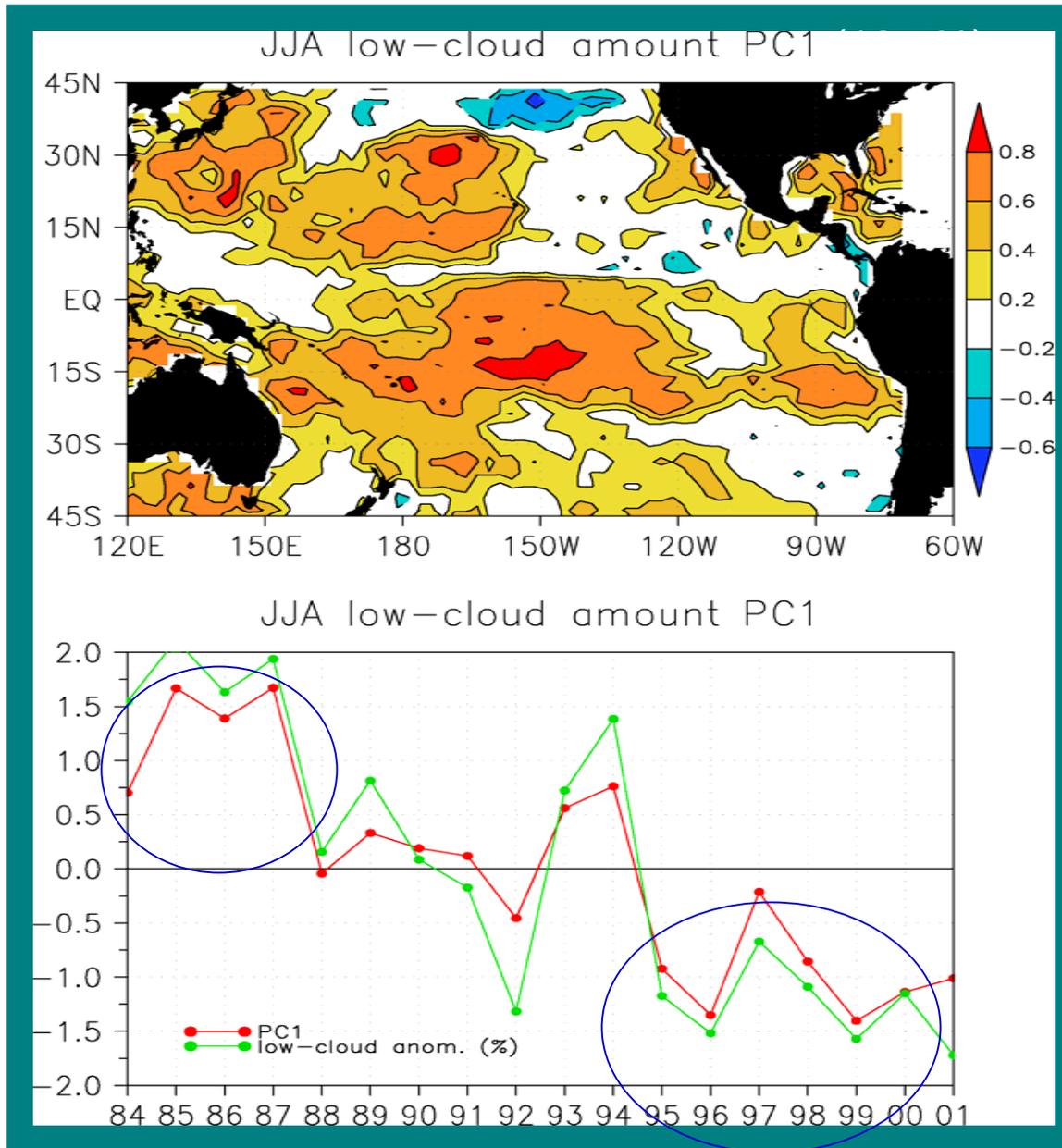
# Composites of 700hPa Specific Humidity



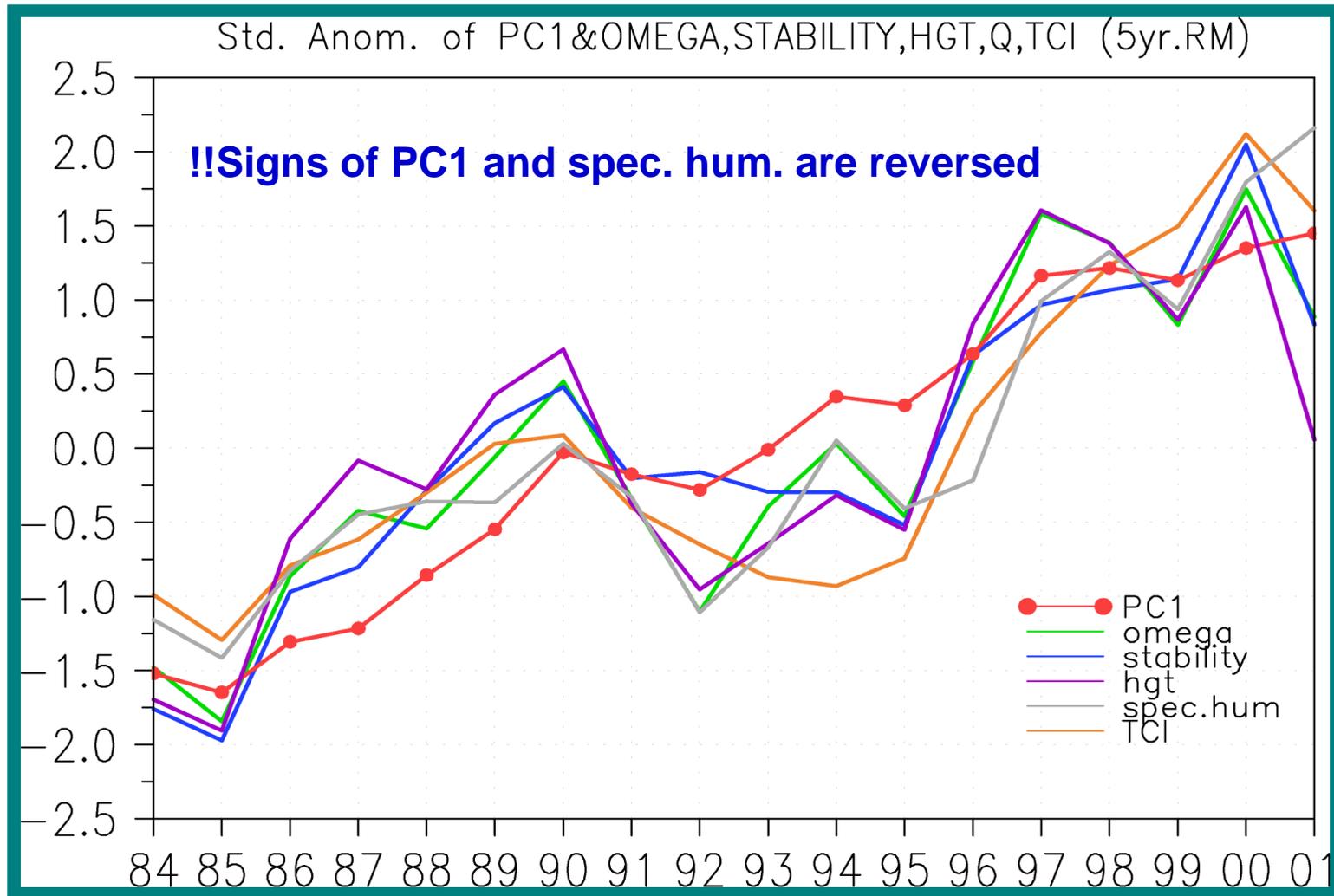
**Pos. cloudiness**  
years: 84,85,86,87

**Neg. cloudiness**  
years: 96,98,99,00

# PC1 for low-cloud anomaly from ISCCP-D2, JJA



# ISCCP PC1 vs. NCEP1 fields averaged over regions of NH and SH ISCCP Maxim



Area average over (150E-150W,0-30N) & (180-90W,0-30S)

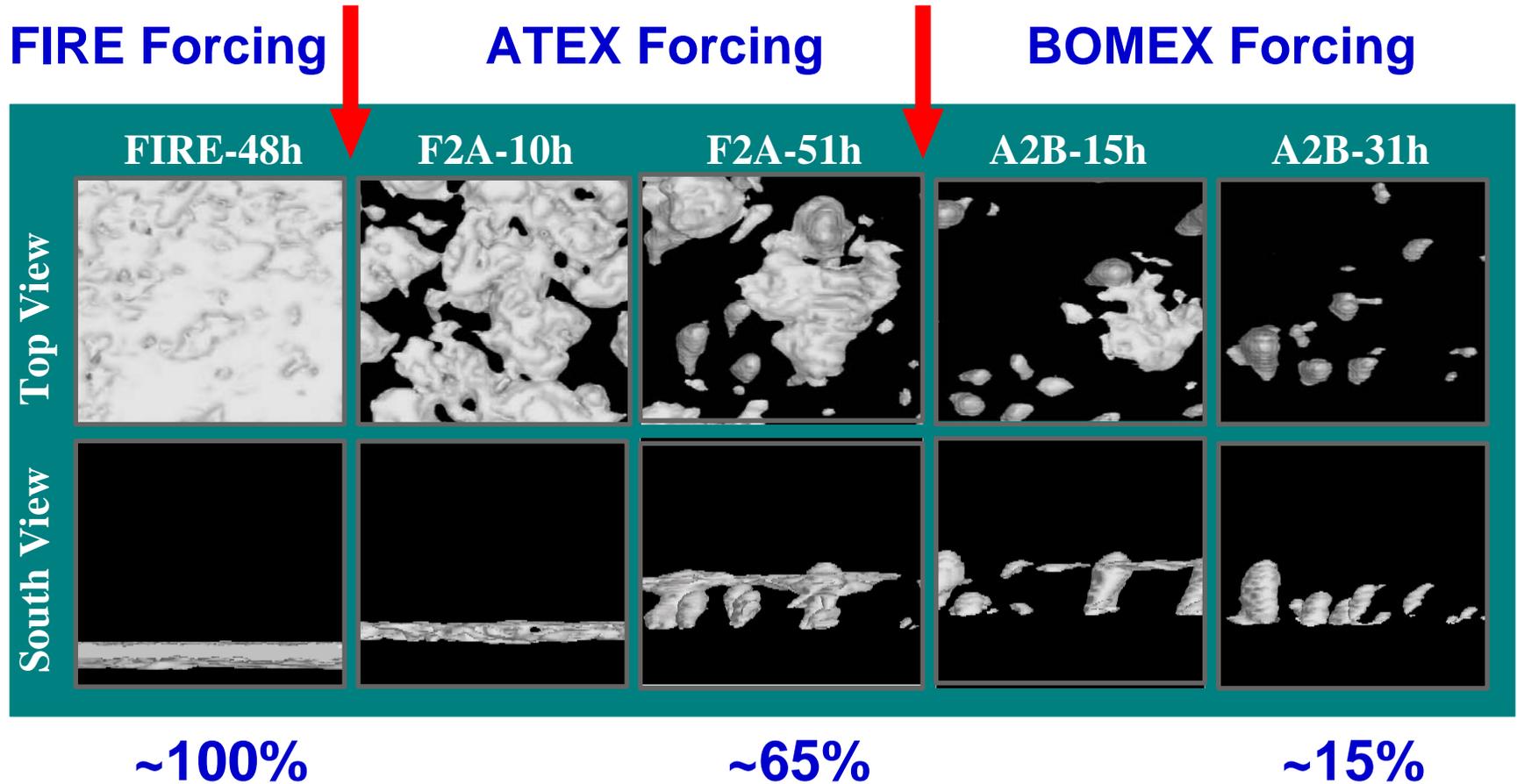
# Summary

- NCEP1 reanalysis for JJA 1983-2001 is characterized by increasing subsidence, surface divergence, decreasing relative humidity in regions of maximum decline in ISCCP D2 low level cloud amount
- This makes intuitive sense. Could an LES make this association quantitative? Could it bound the relative contributions of subsidence, humidity, advective perturbations to the low-cloud trend?

## Equilibrium LES runs

- Model: SAMS 6.2
  - 6km x 6km x 3km domain, 100 m x 100 m x 20 m vertical resolution (plus others)
  - CCM radiation, Smagorinsky sub-grid scale closure
- Test runs:
  - Transitions between established equilibria: FIRE -> ATEX -> BOMEX
  - 1997/1998 El Nino: Climatology plus perturbation

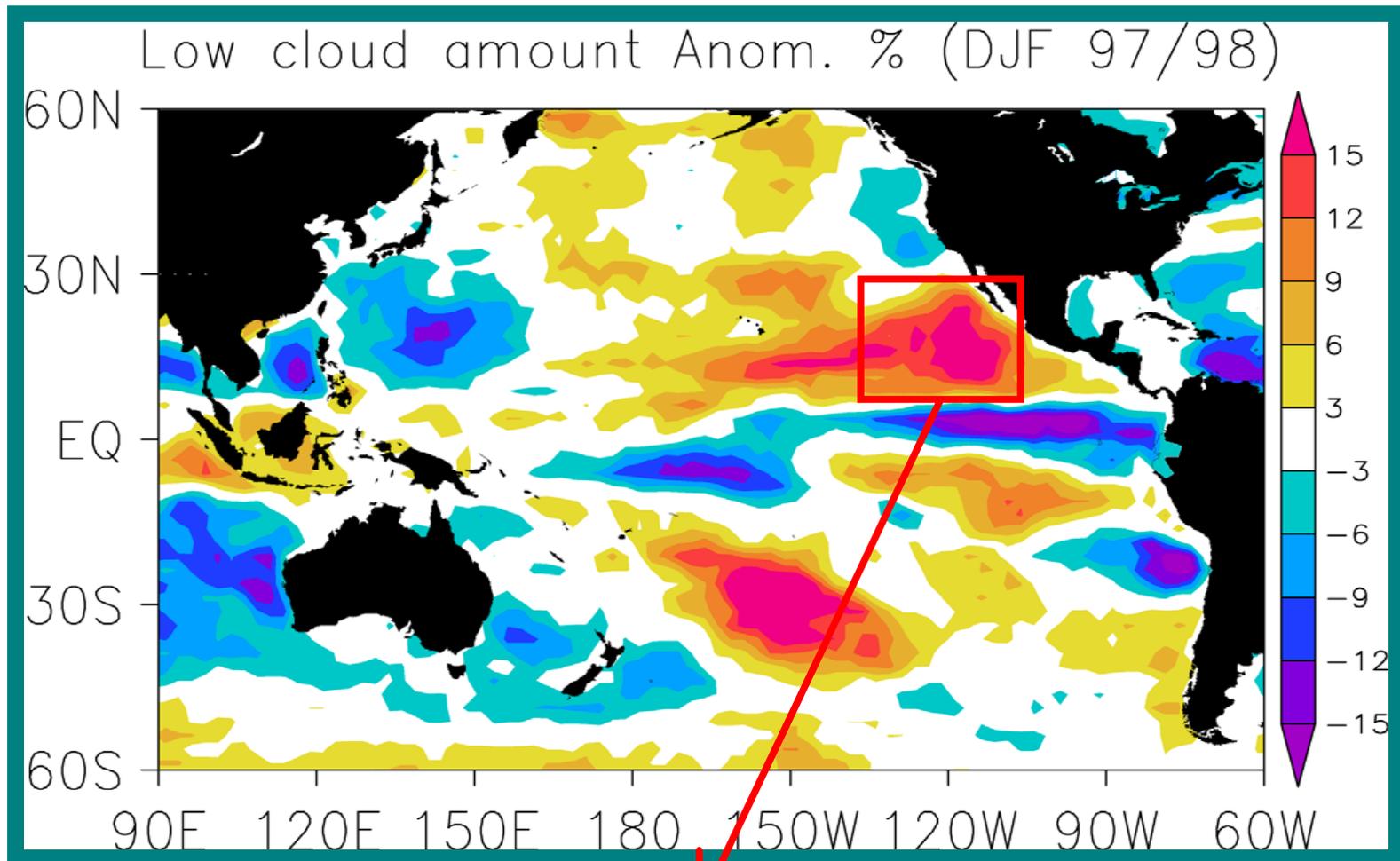
# Cloud Response to abrupt changes of large-scale forcing



## 97/98 El Nino

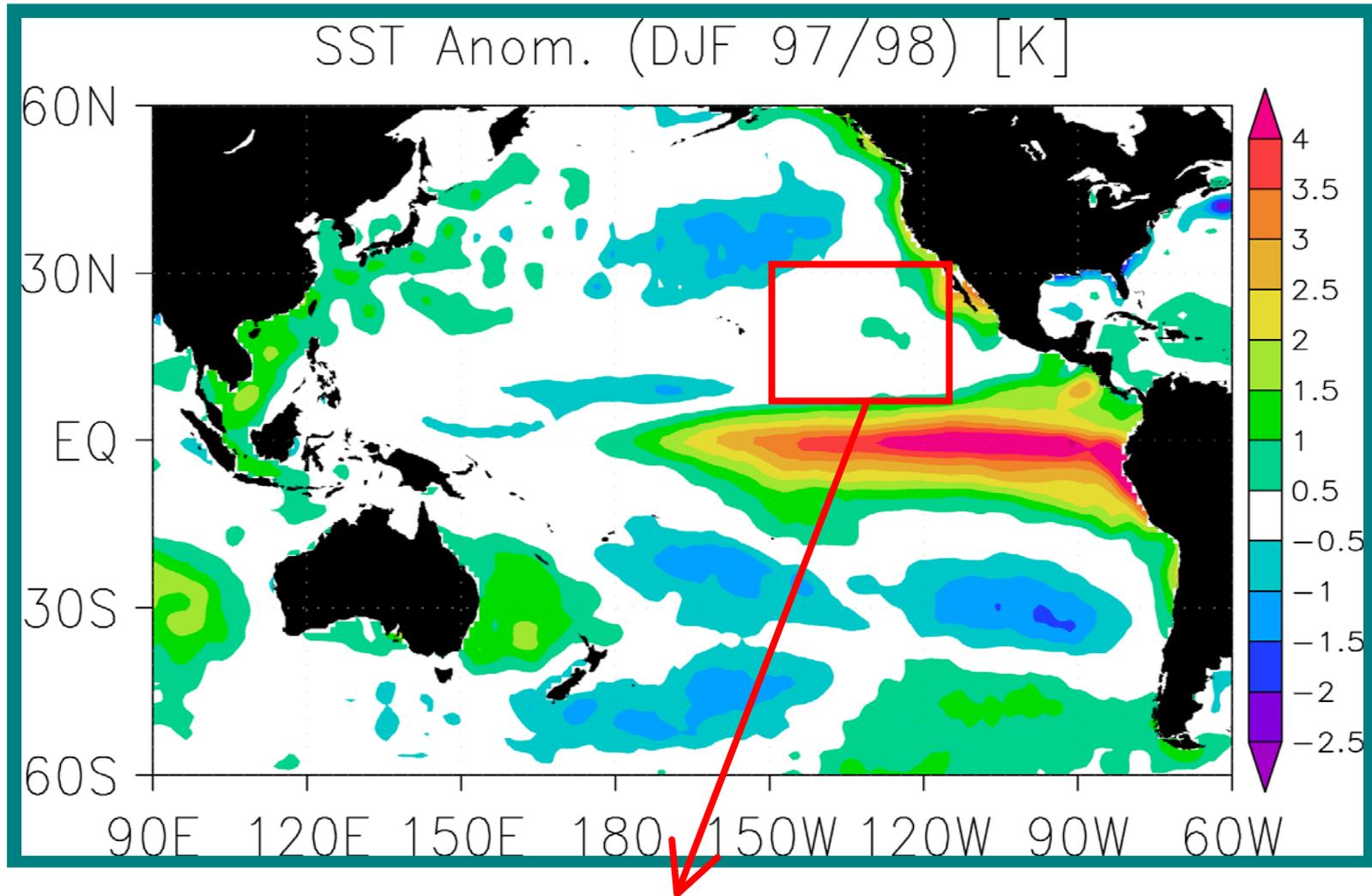
- Average over 110W-130W,10N-25N (area of 97/98 maximum low cloud anomaly).
- Run LES to equilibrium for climatological conditions (with tuned subsidence at cloud top) from NCEP1 1983-2000
- Apply perturbed SST, subsidence, advective tendencies from 97/98, establish new equilibrium

# Low-Cloud Cover Anomalies



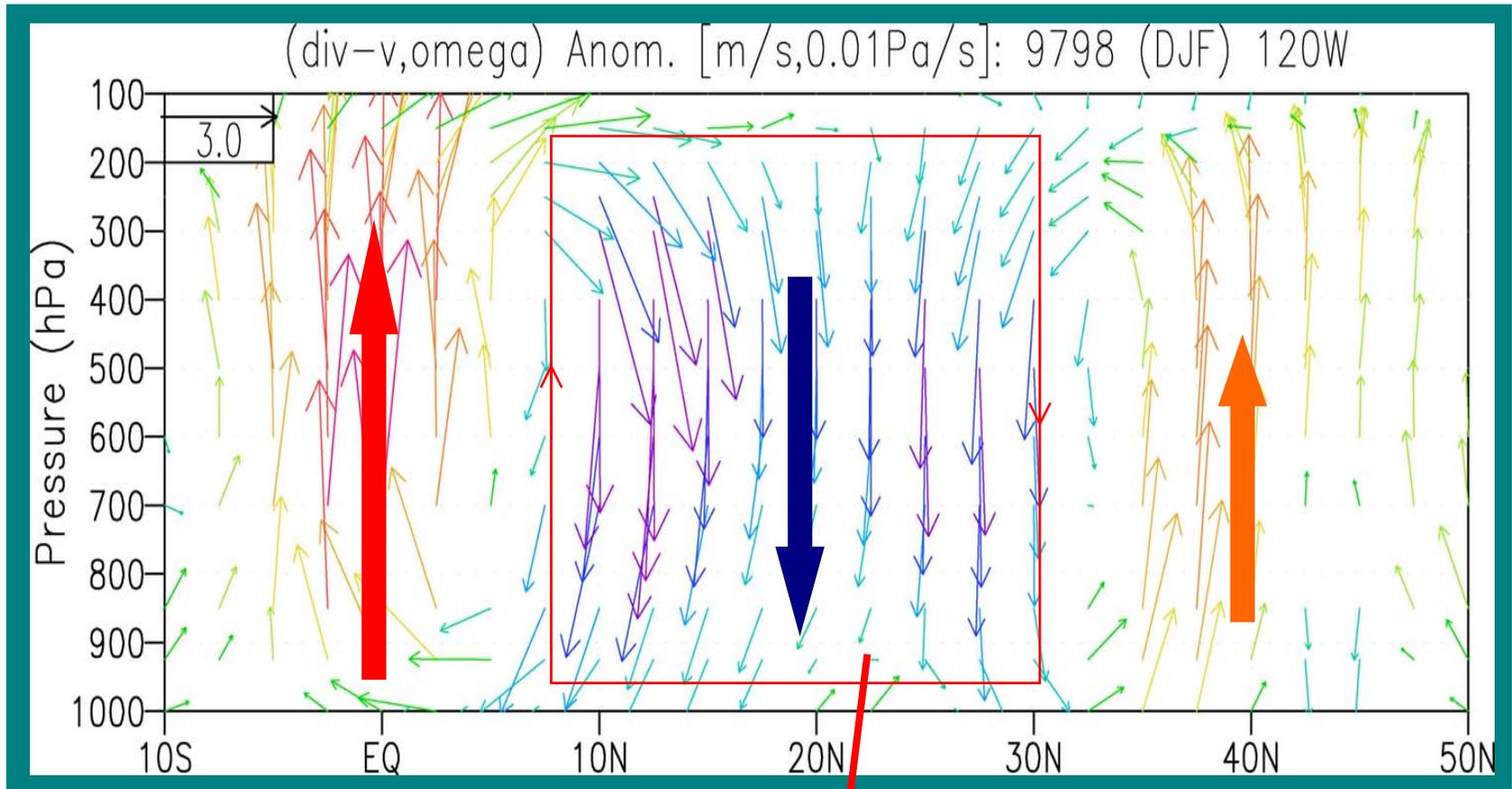
**MBL cloud increased about 5~15%**

# SST anomaly



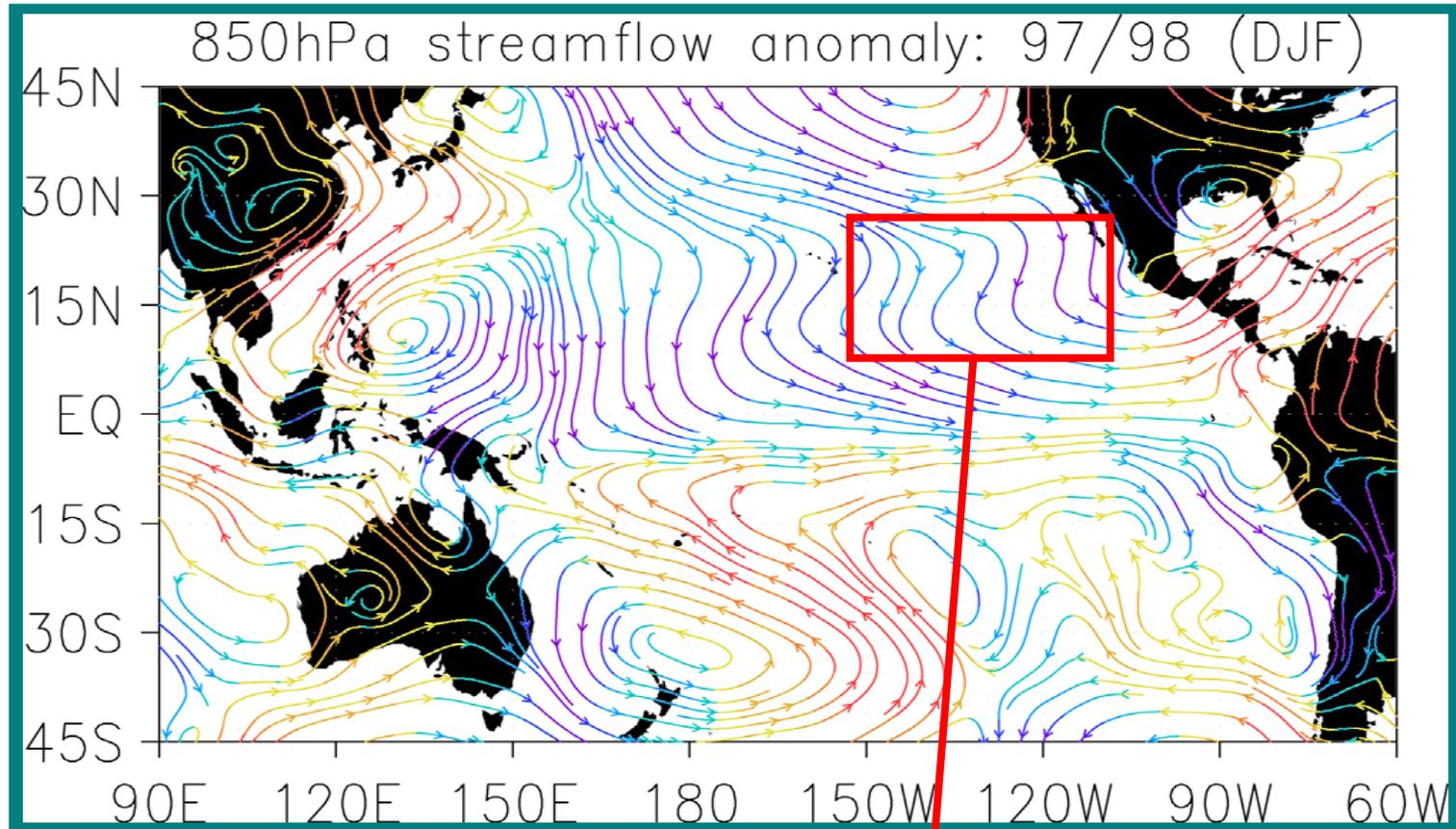
NOAA-OI Area-averaged SST  
anomaly is +0.3K

# Subsidence anomaly



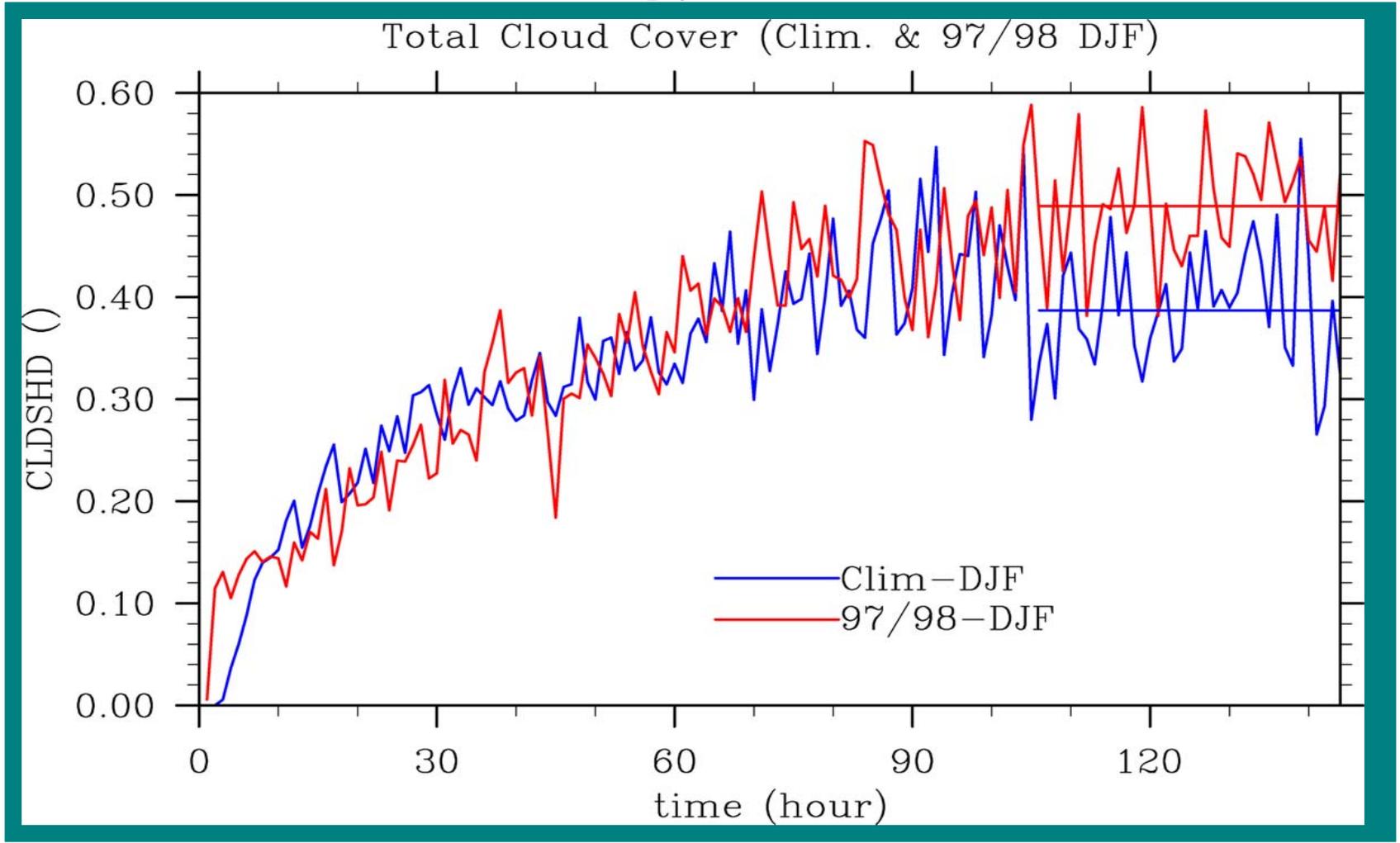
**Subsidence strengthens by 90% in region**

# 850 hPa streamflow anomalies



Increased cold dry  
advection through box

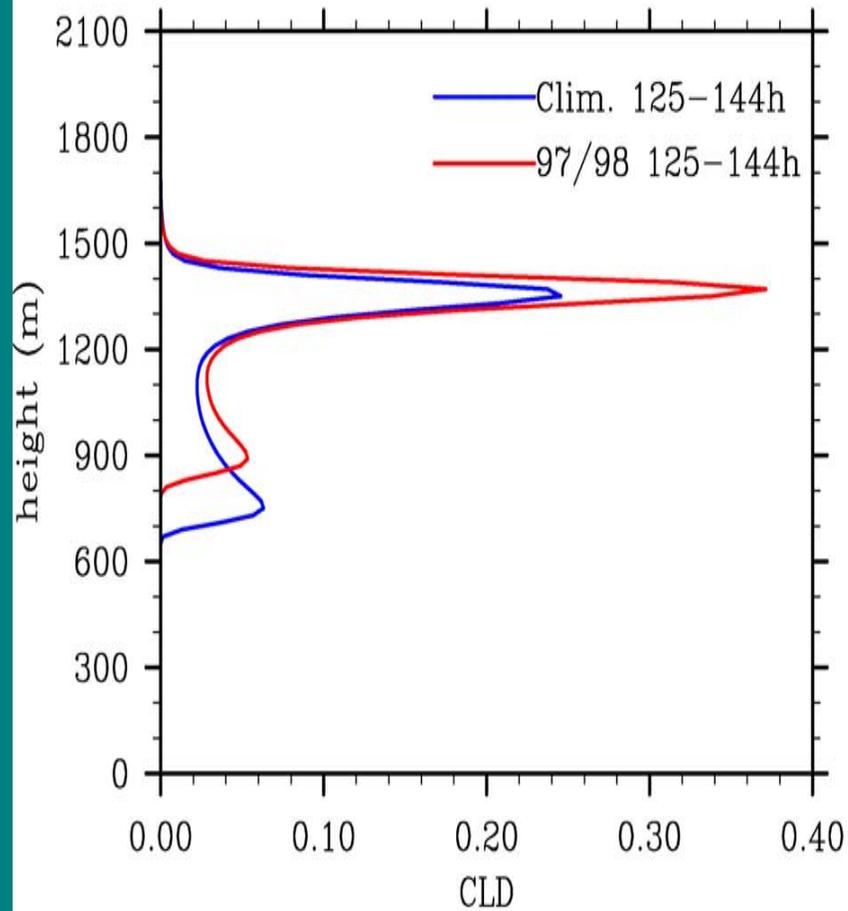
# Climatology vs. El Nino



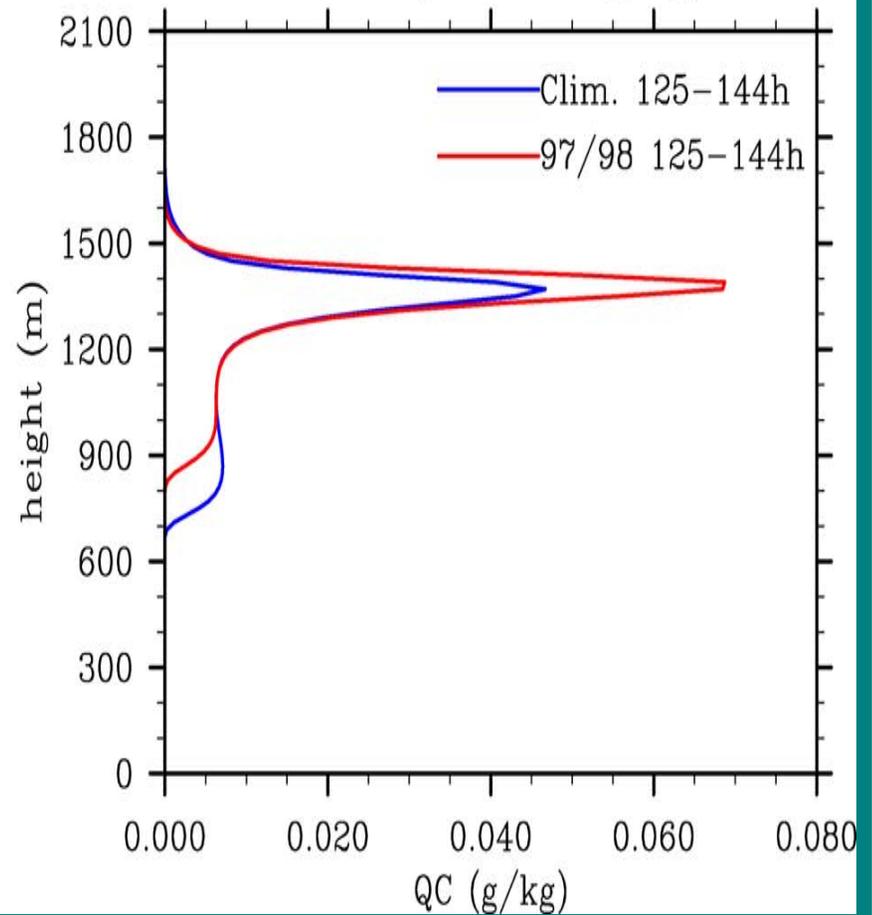
- Simulated cloud cover increase: ~10%

# Cloud Fraction and Cloud Liquid Water

Cloud Fraction



Cloud Liquid Water (g/kg)



# Conclusions

- SAM LES produces robust equilibria for a range of boundary layer cloud types
- Using NCEP1 reanalysis data in the region of maximum cloud cover for the 97/98 El Nino, the model produces a cloud cover increasing from 40% (climatological equilibrium) to 50%, in a shallower layer with near-constant liquid water path
- Todo: Separate influence of advection, inversion characteristics, subsidence rate, drizzle rate (problematic). Further characterize dependence on sub-grid scale and horizontal and vertical grid spacing.

# Scaling and intermittency

- Satellite measurements of power spectra and structure functions for liquid water path/optical depth show an extended inertial subrange for fully cloudy boundary layers but strong intermittency for cloud fractions of 50-80%
- The observed scaling is a statistical property that emerges from an extensive ensemble of images
- Intermittency and corresponding “long-tailed” pdfs imply the need for sampling a very large number of realizations in partly cloud layers to estimate higher moments of cloud statistical distributions

Structure functions  
and power spectra:

$$S_p(\Delta r) = \left\langle (\tau(r + \Delta r) - \tau(r))^p \right\rangle$$

$$S_2(r) = 2 \int_0^\infty [1 - J_0(kr)] E(k) dk$$

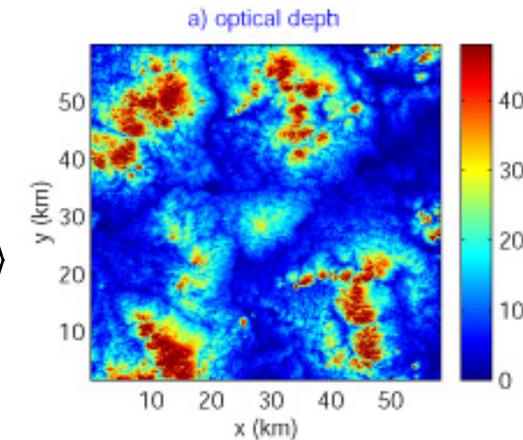
For a passive scalar/  
inertial subrange:

$$S_2 \propto r^{\zeta_2}, \quad \zeta_2 = 2/3$$

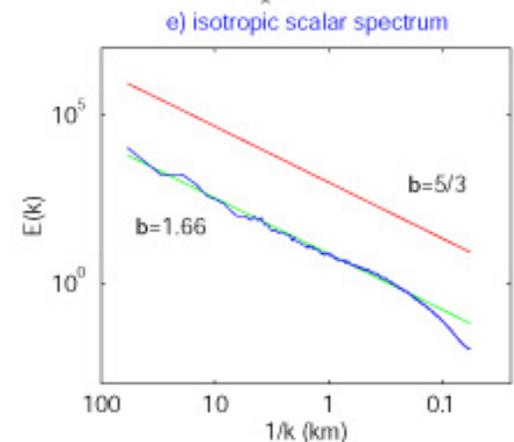
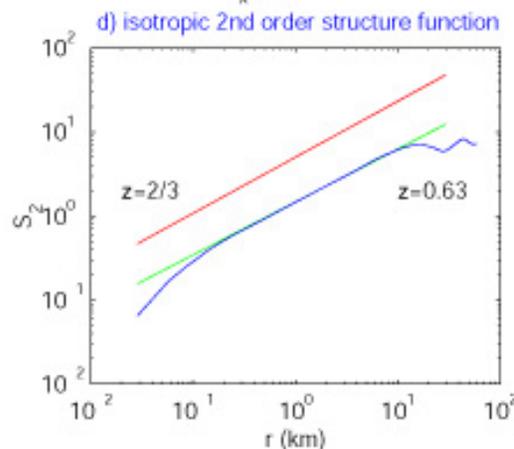
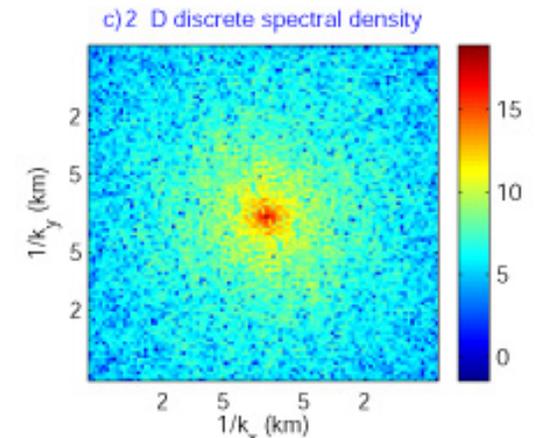
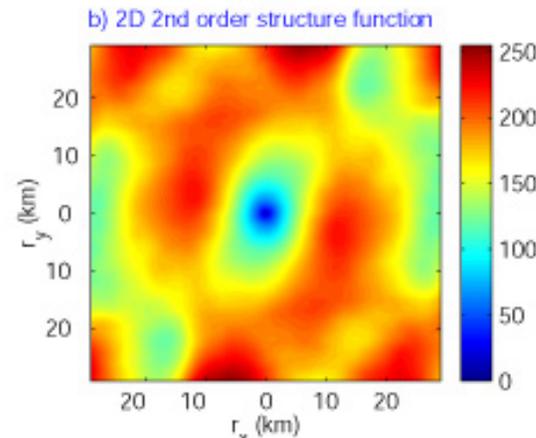
$$E(k) \propto k^{-\beta}, \quad \beta = 5/3$$

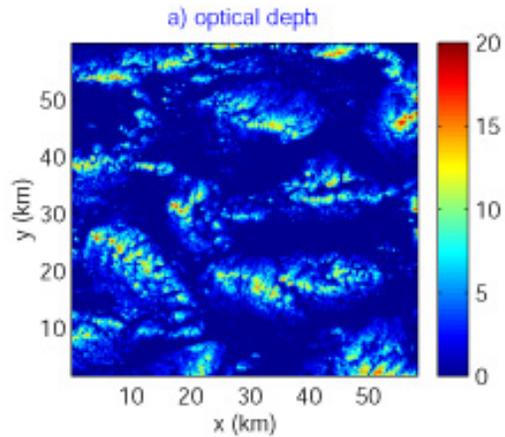
$$\beta = \zeta_2 + 1$$

*Lewis et al., JGR, 2004*

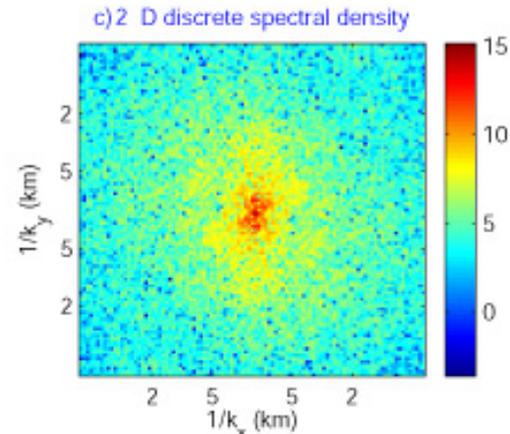
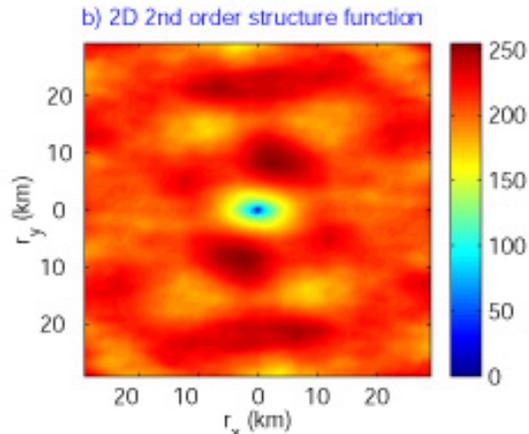
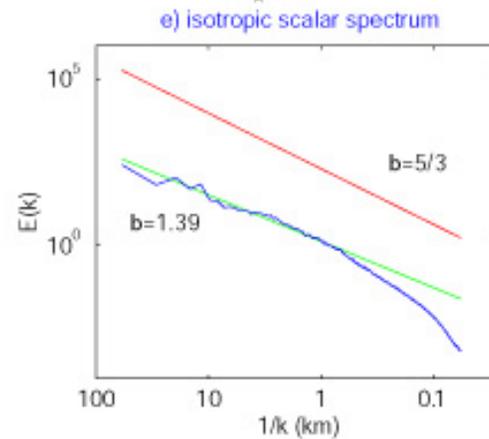
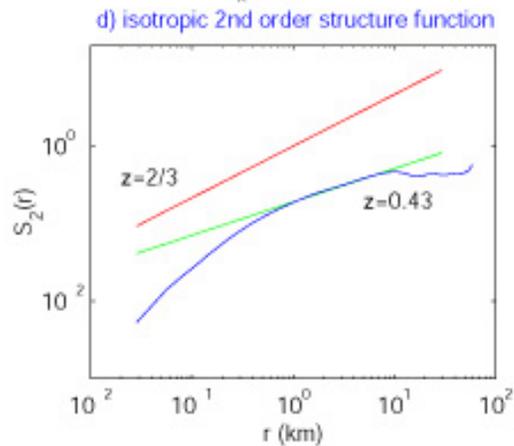


100% cloud cover  
Landsat retrieval,  
stratocumulus  
60 km domain  
30 m pixels

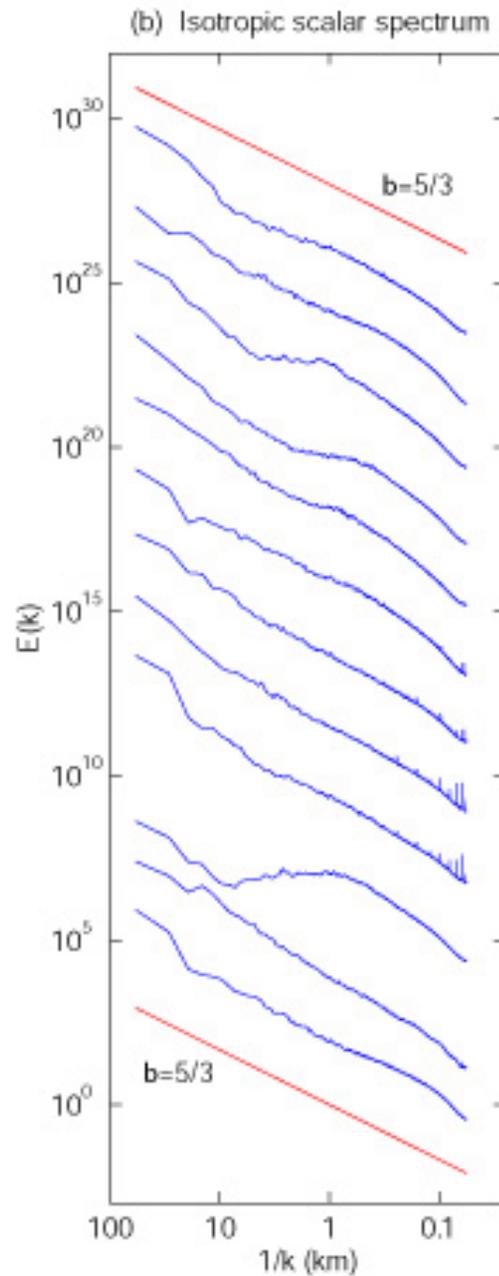
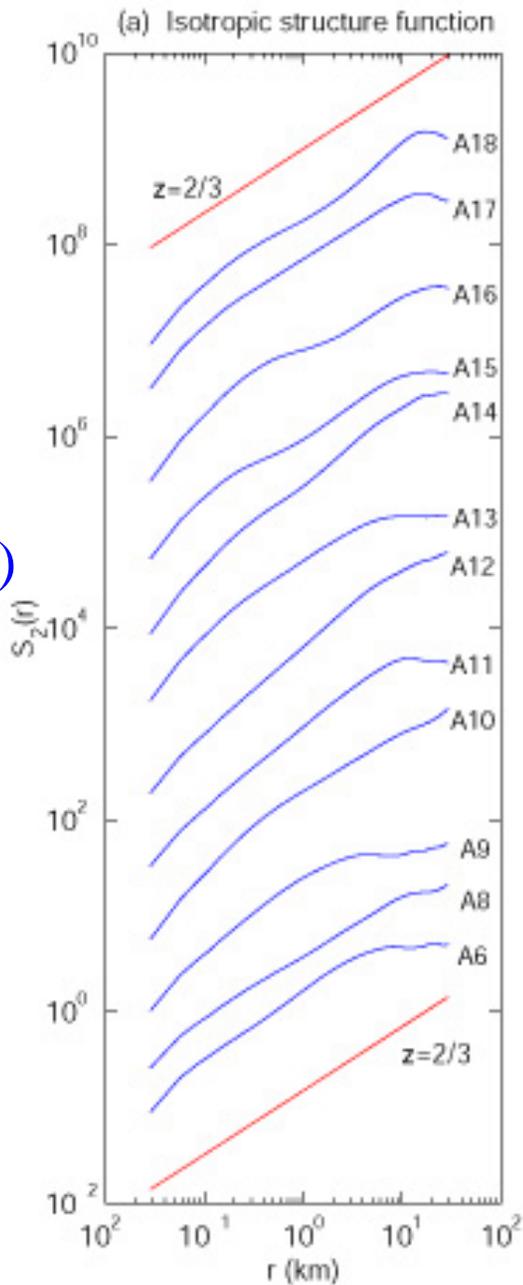


$\tau$ 

50% cloud cover,  
spectrum whitens

 $\langle S_2 \rangle$  $\langle E(\mathbf{k}) \rangle$  $S_2(r)$  $E(k)$

$S_2(r)$

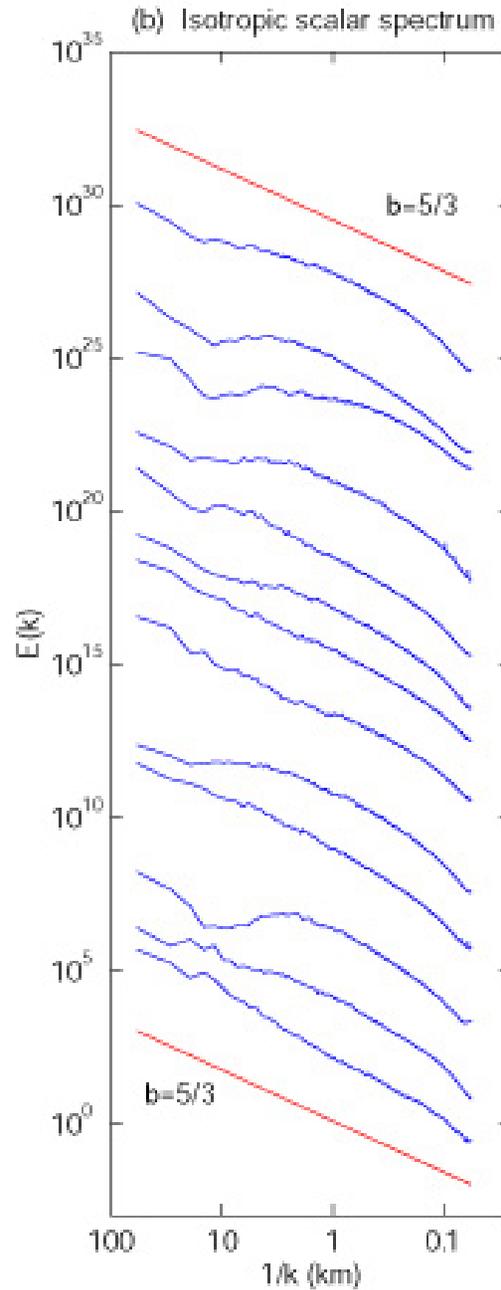
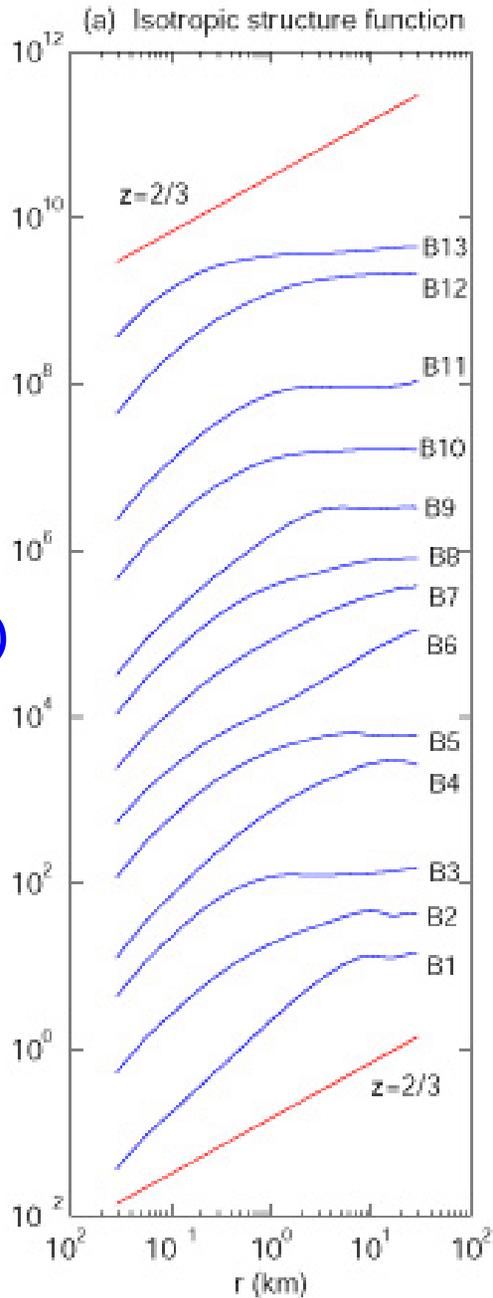


100% cloud frac,  
12 scenes

$E(k)$

Note: Scaling is a  
property of the  
ensemble

$S_2(r)$

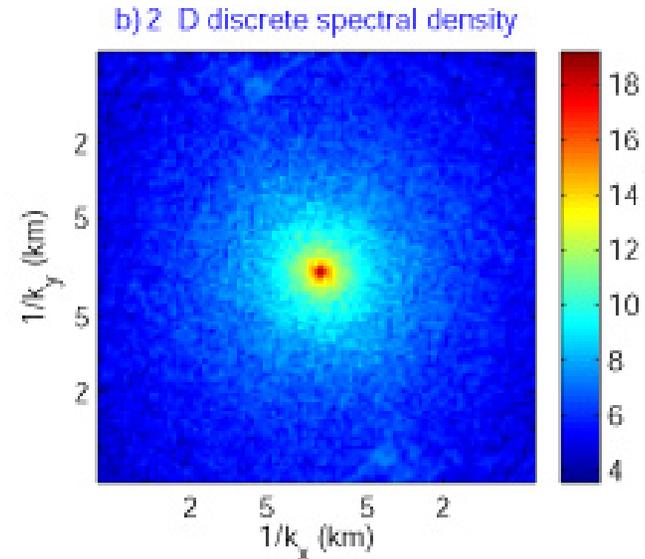
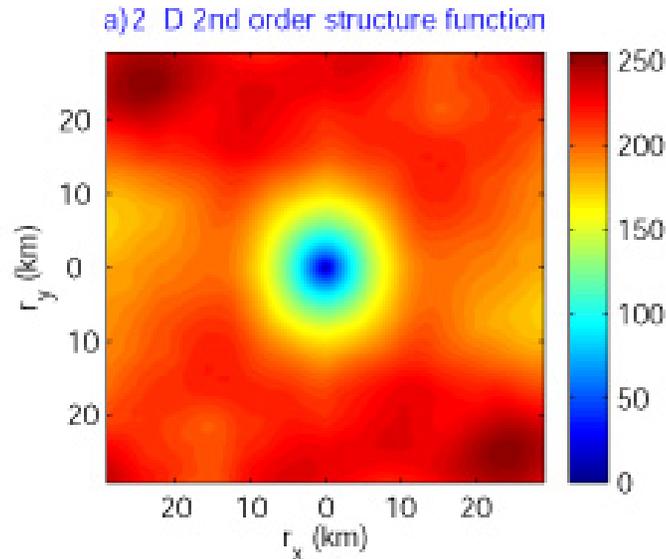


40%-90%  
Cloud fraction  
13 scenes with  
cellular structure

$E(k)$

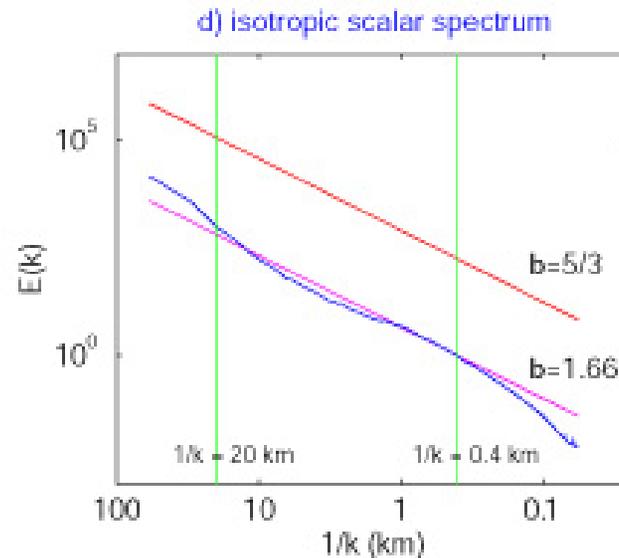
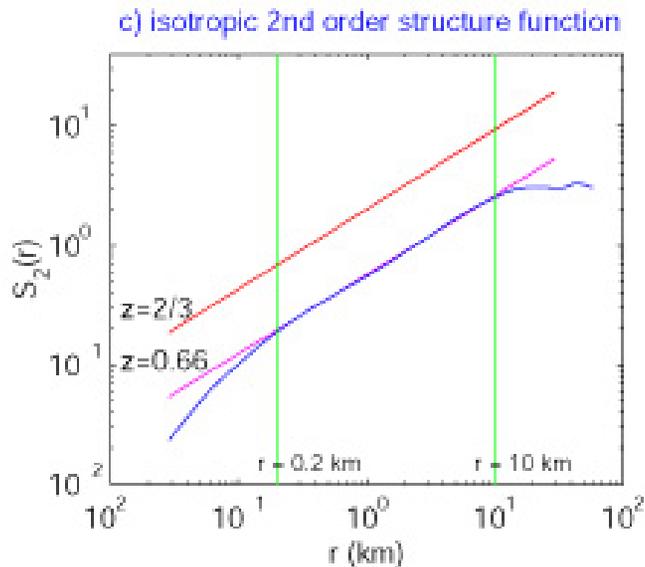
# Ensemble average, 12 scenes 100% cfrac

$\langle S_2 \rangle$



$\langle E(\mathbf{k}) \rangle$

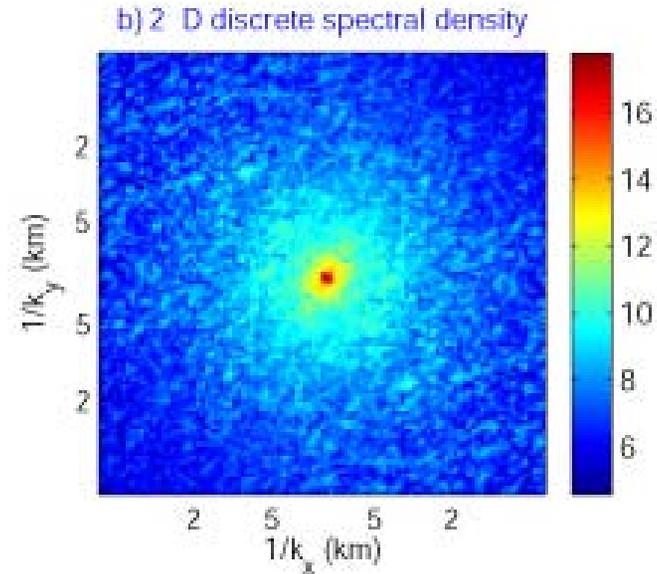
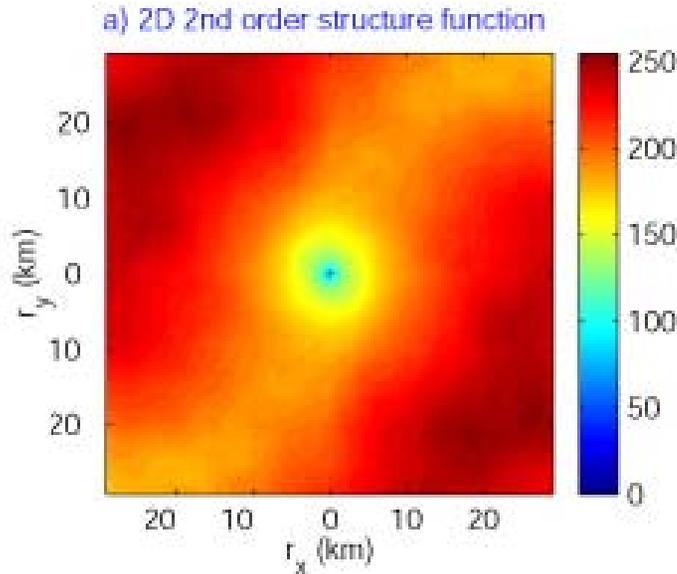
$S_2(r)$



$E(k)$

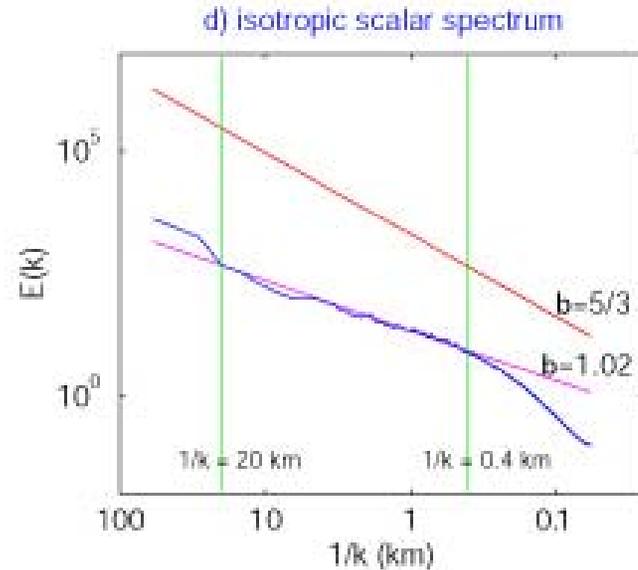
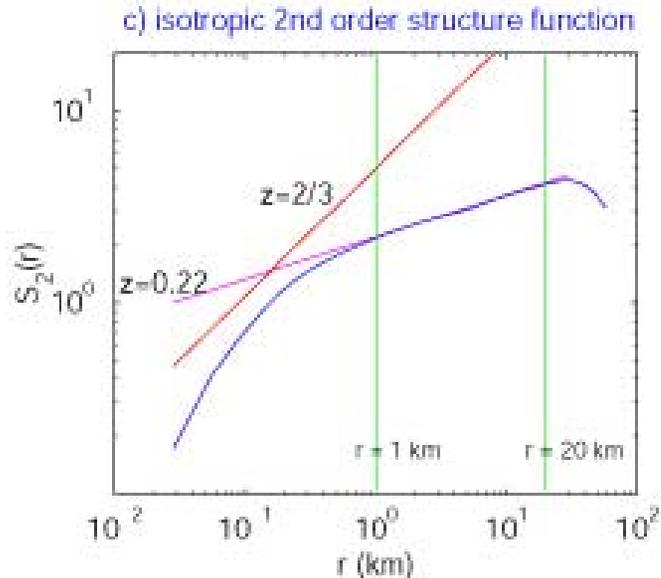
# Ensemble average, partly cloudy scenes

$\langle S_2 \rangle$



$\langle E(\mathbf{k}) \rangle$

$S_2(r)$



$E(k)$

# Scaling: higher order statistics: $S_p \propto r^{\zeta_p}$

$\zeta_p$

