Bulk Concepts & Integral Constraints as Applied to Atmospheric Boundary Layers

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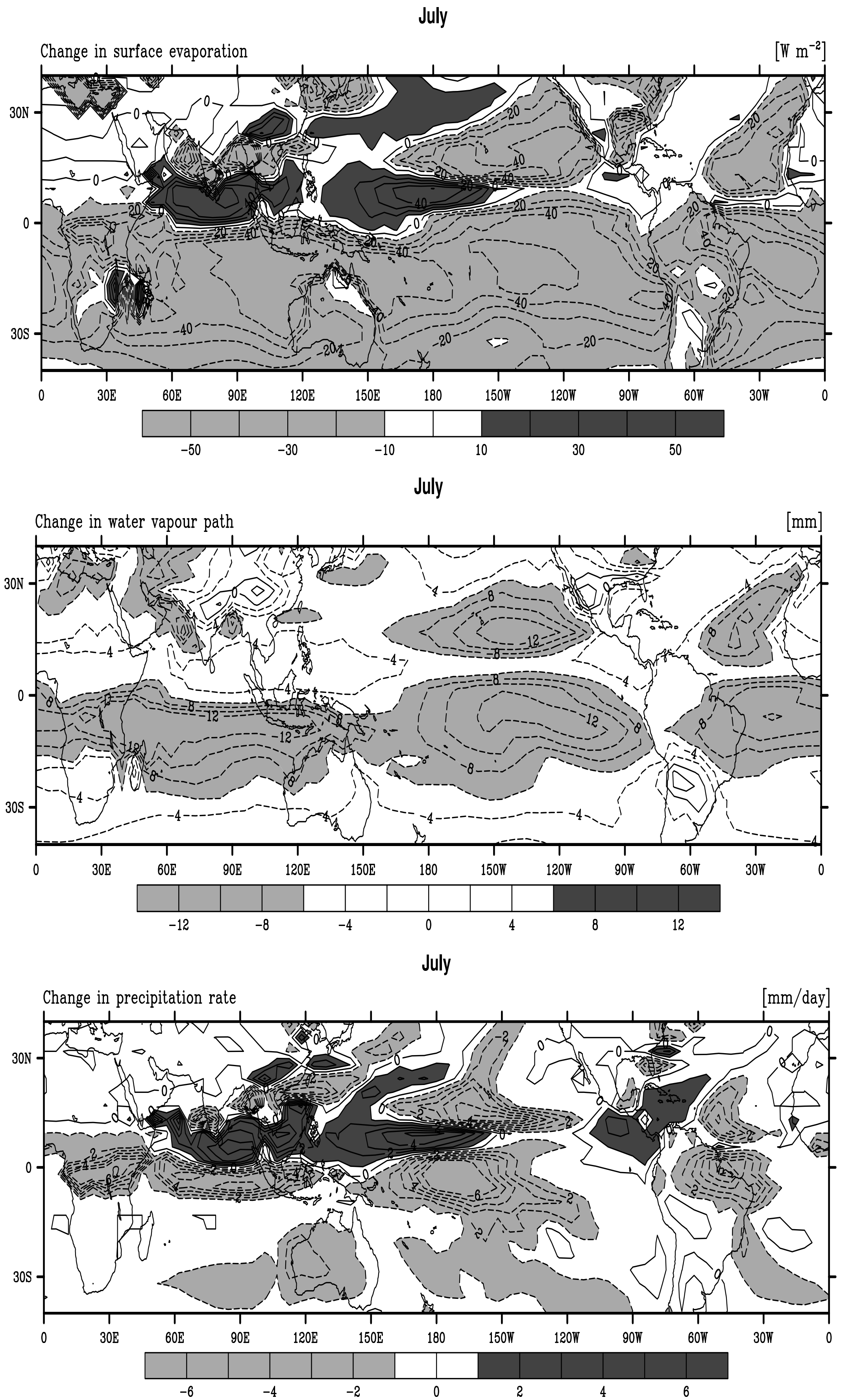
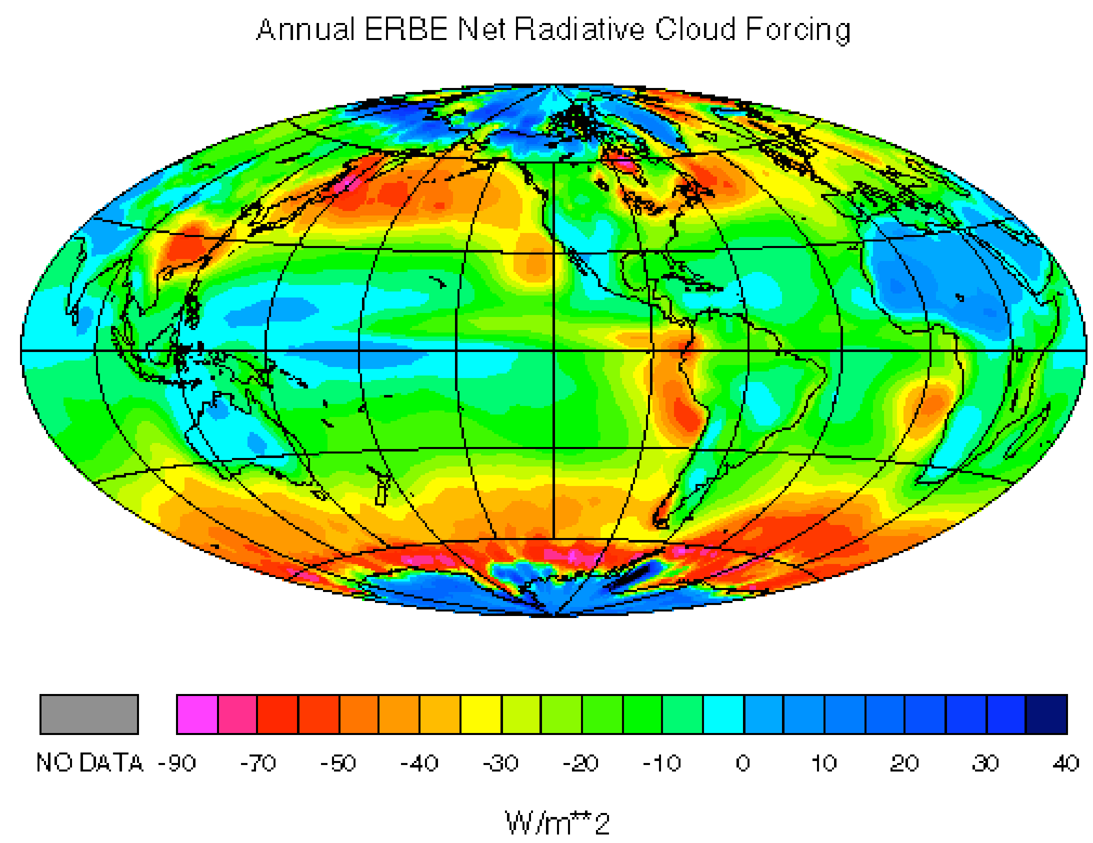
thanks to yunyan zhang

The Shallow Cumulus Humidity Throttle



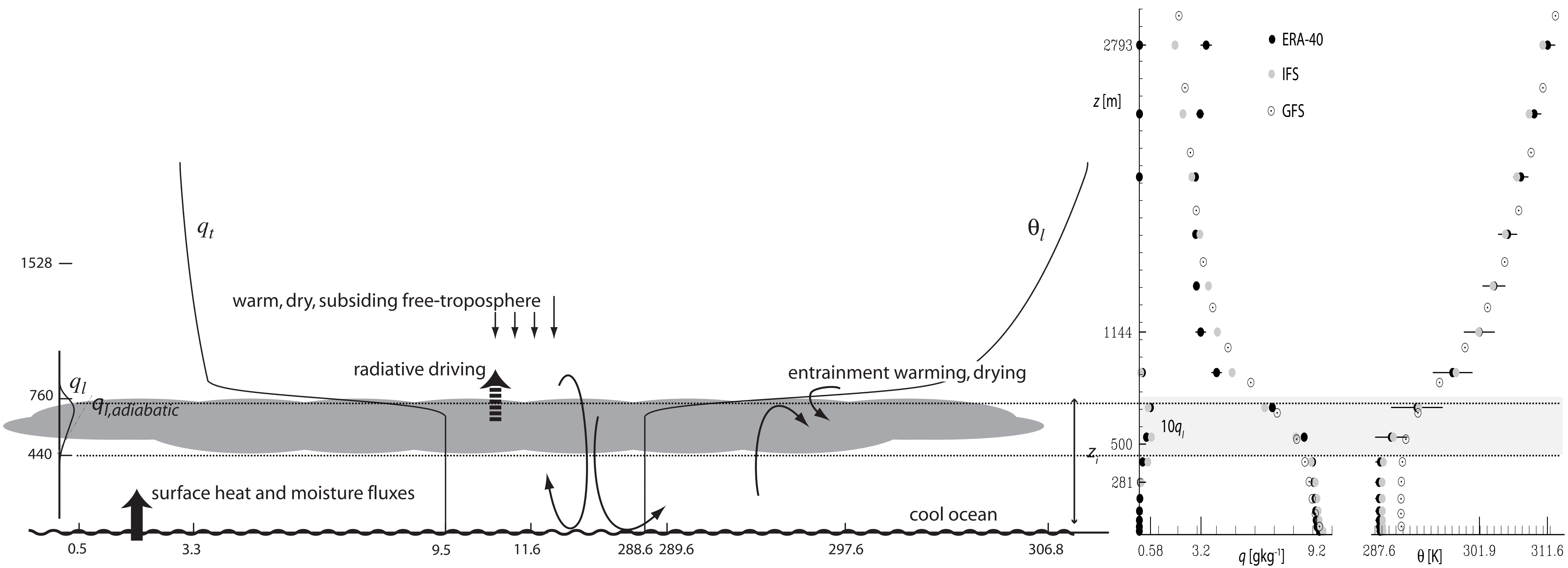
Neggers, Neelin and Stevens, 2005.

Cloud Radiative Forcing



(c/o dennis hartmann)

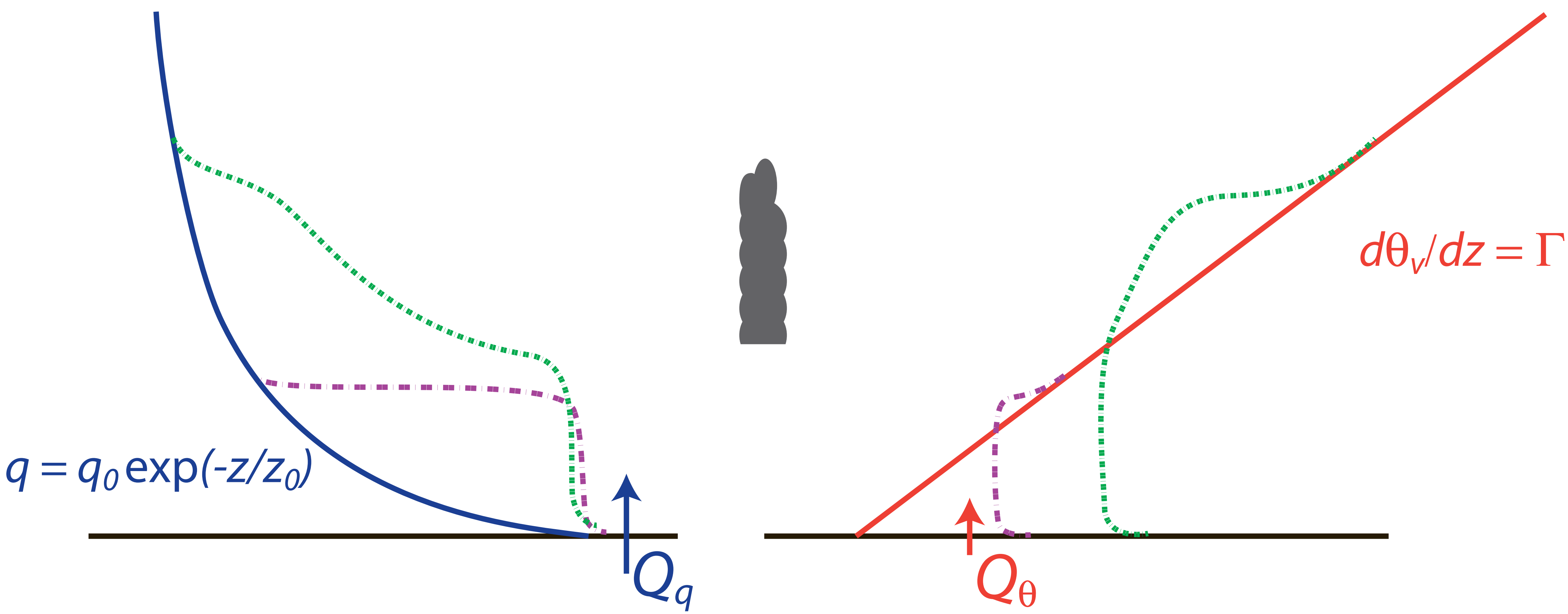
July 2001, near 120W and 30N



ERA-40, IFS and GFS diffuse the top of the PBL too much
GFS has a significant PBL warm bias (3K)
GFS has essentially no cloud, liquid water a factor of 10 too small in IFS/ERA-40

Stevens, et al., 2005.

Trade-Wind Analog to the Dry Convective PBL



Bulk Description

Defining the operators:

$$\widehat{\phi}(x, y, t) \equiv \frac{1}{h_+} \int_0^{h_+} \overline{\phi}(x, y, z, t)\,\mathrm{d}z \tag{1}$$

$$\Delta_+\phi \equiv \phi_+ - \widehat{\phi} \tag{2}$$

$$\Delta_0\phi \equiv \widehat{\phi} - \phi_0 \tag{3}$$

$$\Delta\phi \equiv \Delta_+\phi + \Delta_0\phi. \tag{4}$$

Assuming that (i) fluxes of ϕ are horizontally homogeneous; and (ii) vertical fluctuations in scalar profiles are independent of such fluctuations in the horizontal wind, the conservation law for $\widehat{\phi}$ becomes

$$h\frac{D\widehat{\phi}}{Dt} - \Delta_+\phi\left[\frac{Dh}{Dt} + \mathcal{D}h\right] = -\Delta\overline{w'\phi'} - \Delta F_\phi \tag{5}$$

where

$$\frac{D}{Dt} \equiv \partial_t + \widehat{\mathbf{u}} \cdot \nabla \quad \text{and} \quad \mathcal{D} \equiv \nabla \cdot \widehat{\mathbf{u}}.$$

Stratocumulus Solutions

In general,

$$V = C_d \|\mathbf{u}\| \tag{1}$$

For stratocumulus

$$M = \Delta F_q = 0 \tag{2}$$

$$E = \alpha \frac{\Delta F_s}{\Delta_+ s} \tag{3}$$

Steady-state solutions for this system take the form

$$h_\infty = h_* \left(\frac{\alpha\sigma}{1 + \sigma - \alpha} \right), \tag{4}$$

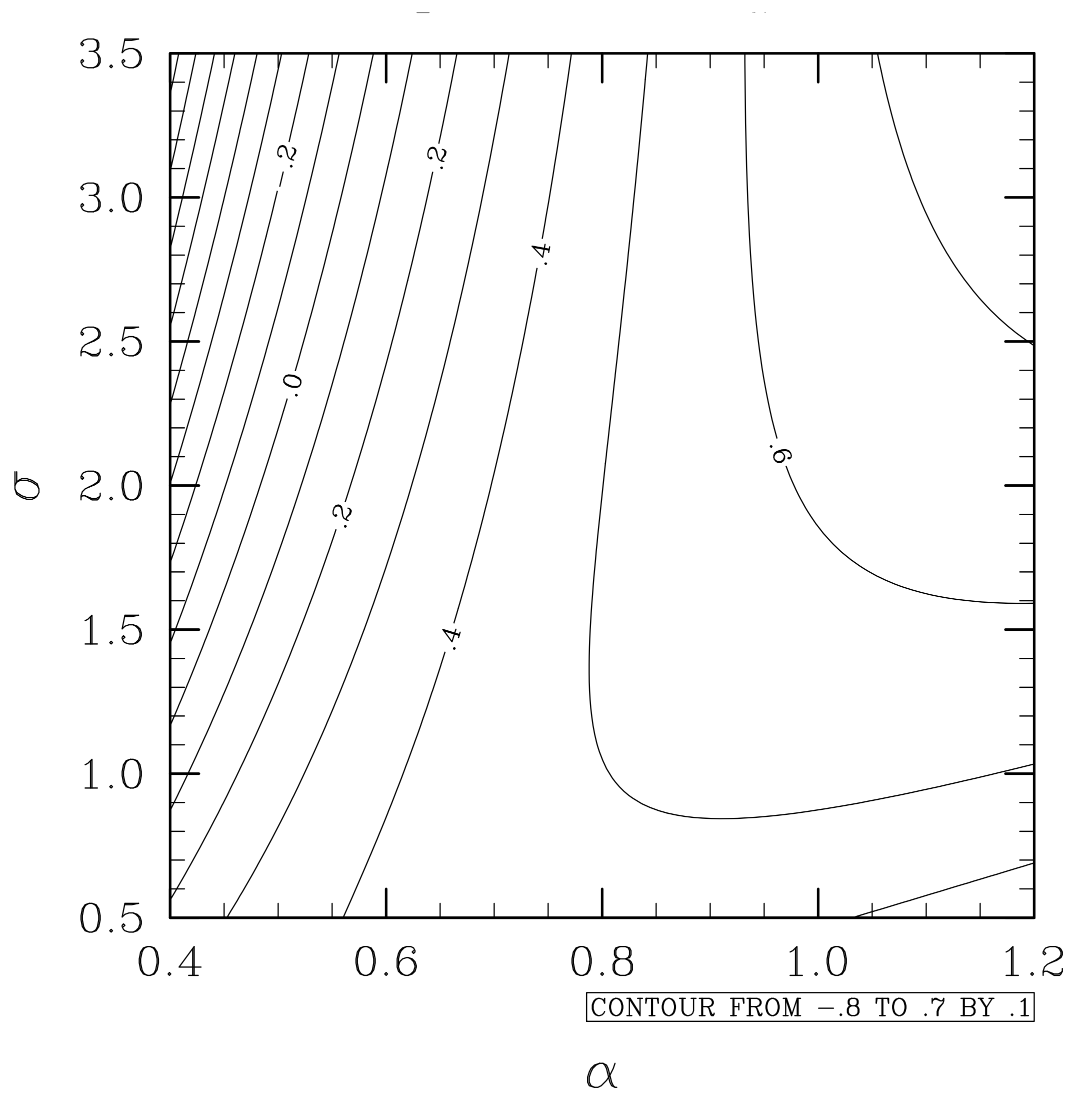
$$s_\infty = s_0 - \Delta s \left(\frac{1 - \alpha}{\sigma} \right), \quad \text{and} \tag{5}$$

$$q_\infty = q_0 + \Delta q \left(\frac{\alpha}{1 + \sigma} \right), \tag{6}$$

where

$$h_* = \frac{\Delta F}{\mathcal{D} \Delta s} \quad \text{and} \quad \sigma = \frac{V \Delta s}{\Delta F}. \tag{7}$$

Non-dimensional cloud base height



Trade-Cumulus Solutions (Betts/Ridgway)

For the entirety of the trade-cumulus layer, again $M = 0$ and V is as before, where now substituting for E from the steady state mass balance

$$0 = \mathcal{D}h\Delta_+ s + \overline{w's'}_0 - \Delta F \quad (1)$$
$$0 = \mathcal{D}h\Delta_+ q + \overline{w'q'}_0. \quad (2)$$

$$\overline{\phi} = \begin{cases} \phi_m & z < \eta \\ \phi_m + \left(\frac{z-\eta}{h-\eta}\right)\phi_- & z \geq \eta \end{cases} \quad \text{where} \quad \phi_- = (1-\beta_-)\phi_m + \beta_-\phi_+; \quad (3)$$

where η is the cloud-base height, and $\phi_- \equiv \overline{\phi}_{z=h_-}$ measures the state variable properties just below cloud top. Integrating over the layer yields

$$\widehat{\phi} = \phi_m + \zeta(\phi_+ - \phi_m) \quad \text{where} \quad \zeta = \frac{\beta_-}{2}\left(1 - \frac{\eta}{h}\right). \quad (4)$$

System becomes

$$0 = \mathcal{D}h(1-\zeta)(s_+ - s_m) + V(s_0 - s_m) - \Delta F, \quad (5)$$
$$0 = \mathcal{D}h(1-\zeta)(q_+ - q_m) + V(q_0 - q_m). \quad (6)$$

Trade-Cumulus Solutions (cont)

and closure is determined by

$$\mathcal{D}\eta(\overline{s}_{z=\eta+\epsilon} - s_m) = -\kappa V(s_0 - s_m), \tag{7}$$

Yielding equilibrium solutions

$$s_m = s_0\left(1 - \frac{\gamma}{1+\kappa}\right), \tag{8}$$

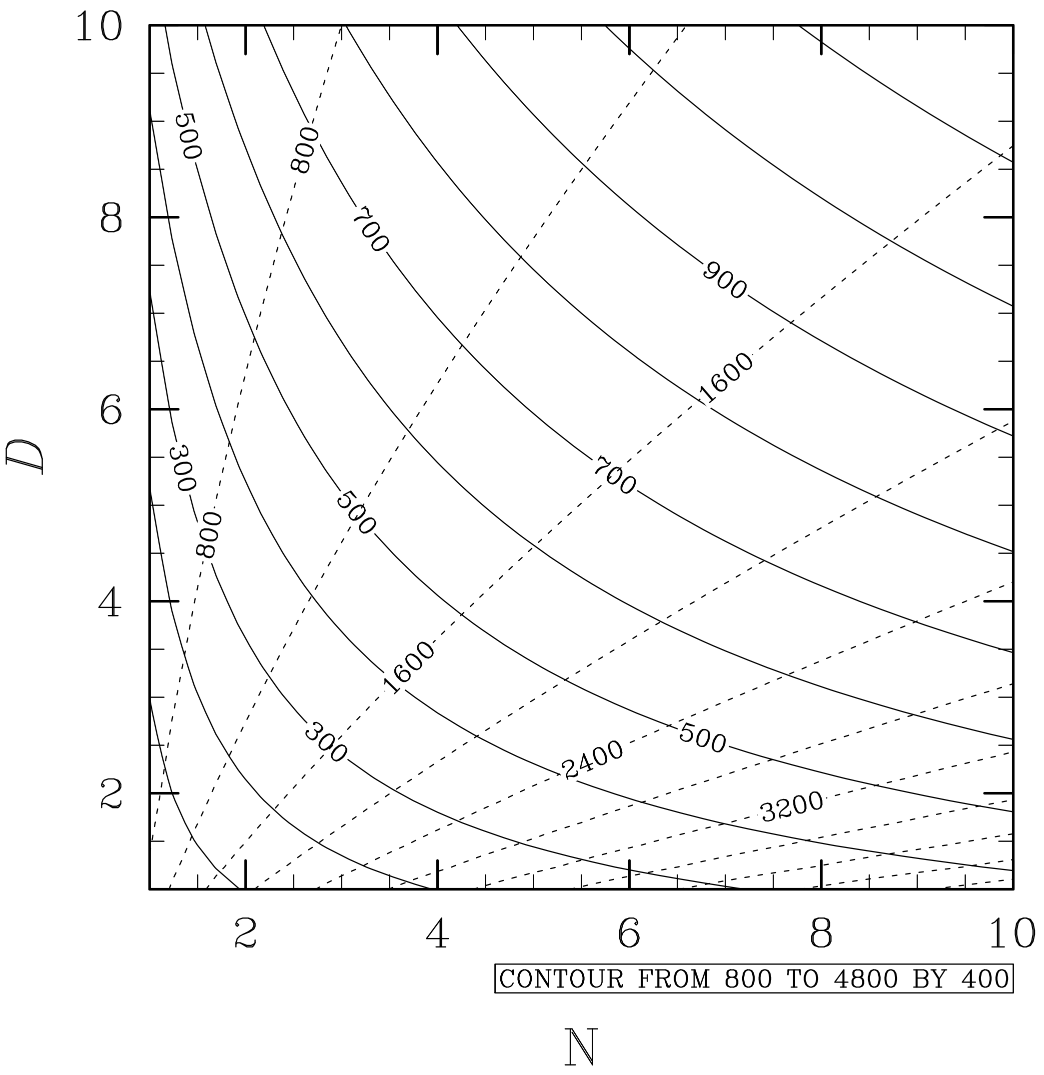
$$q_m = \frac{q_0 + Rq_+}{1+R}, \quad \text{and} \tag{9}$$

$$s_+ = s_0\left[1 - \frac{\gamma}{R}\left(\frac{1+R}{1+\kappa} + N\right)\right] \tag{10}$$

where ideally the non-dimensional parameters

$$\gamma = \frac{\Delta_m F}{s_0 V} \quad N = \frac{\Delta F}{\Delta_m F} \quad R \equiv \frac{\mathcal{D}h}{V}(1-\zeta) \tag{11}$$

Cloud base height and cloud top height



Trade-Cumulus Solutions (Subcloud layer)

Modeling the subcloud layer requires some way to detrmine ϕ_+ given values in the free troposphere. Assuming a mixing line model yields

$$\phi_+ = \beta_{\phi_+}(\phi_f - \widehat{\phi}) \quad (1)$$

$$E = -\kappa B_0/\Delta_+ b, \quad (2)$$

with

$$\Delta_+ b \equiv b_+ - \widehat{b} = \frac{g}{s_0}[\Delta_+ s + 0.608 s_0 \Delta_+ q] \quad \text{and} \quad (3)$$

$$\mathcal{B}_0 = -\frac{gV}{s_0}[\Delta_0 s + 0.608 s_0 \Delta_0 q] \quad (4)$$

Modeling the cloud-base mass flux as

$$M = \mathcal{A} w_* \quad (5)$$

Look for cloud free solutions

$$
\begin{aligned}
h_\infty &= \frac{E}{\mathcal{D}}, && (6)\\
\widehat{s}_\infty &= \frac{Vs_0 + \beta_+ E s_f - \Delta F}{V + \beta_+ E}, \quad \text{and} && (7)\\
\widehat{q}_\infty &= \frac{Vq_0 + \beta_+ E q_f - h\widehat{\mathbf{u}} \cdot \nabla q}{V + \beta_+ E}, && (8)
\end{aligned}
$$

where

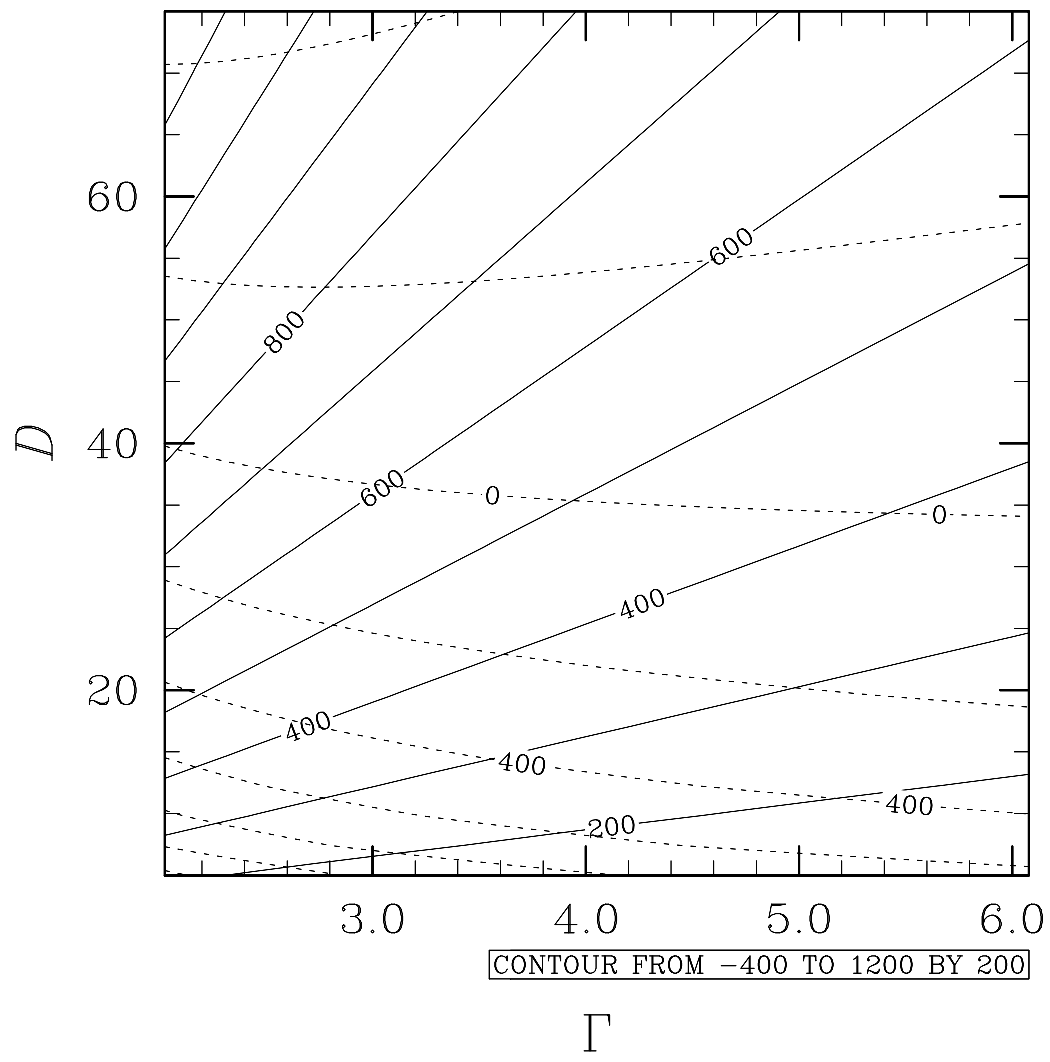
$$
E = \frac{\kappa}{\beta_+} V \left(\frac{\Delta F + 0.608 s_0 h \widehat{\mathbf{u}} \cdot \nabla q}{\Delta F_s + 0.608 s_0 h \widehat{\mathbf{u}} \cdot \nabla q + (1+\kappa) V (\Delta s + 0.608 s_0 \Delta q)} \right). \quad (9)
$$

For cloudy solutions, hoosing $M = E - D\eta$ must be true in equilibrium, in which case the equilibrium cloud fraction is just

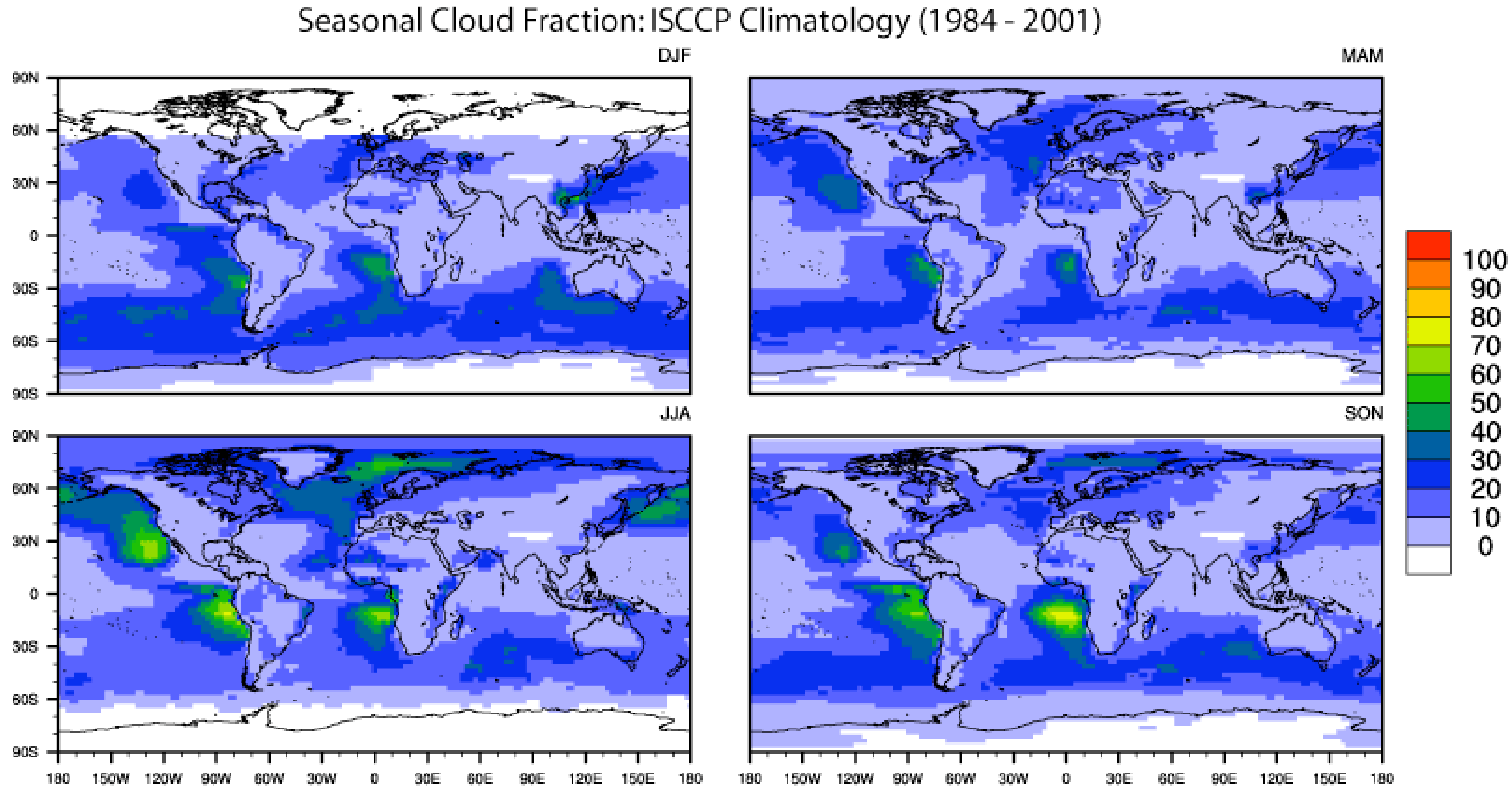
$$
\mathcal{A} = \frac{E - \mathcal{D}\eta_\infty}{w_*}. \quad (10)
$$

For typical values of $E \approx 1$ cm s^{-1}, $D = 3^{-6}$ ss^{-1}, $\eta = 500$ m and $w_* = 0.6$ mss^{-1}, $E \gg \mathcal{D}\eta$, and $\mathcal{A} \approx E/w_* \approx 0.02$ which might explain why cloud fraction is order a few percent.

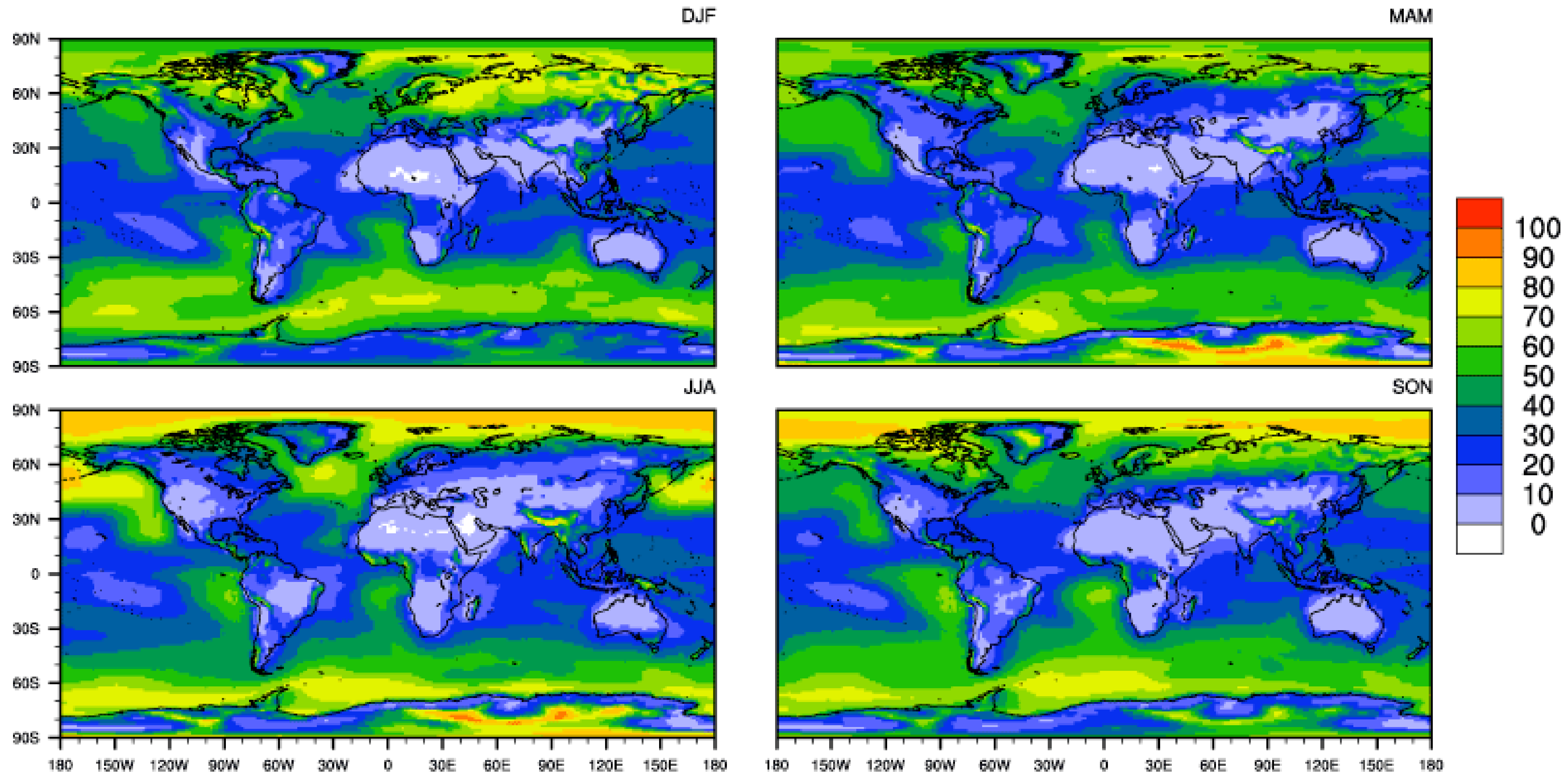
Cloud base height and cloud thickness (for M=0)



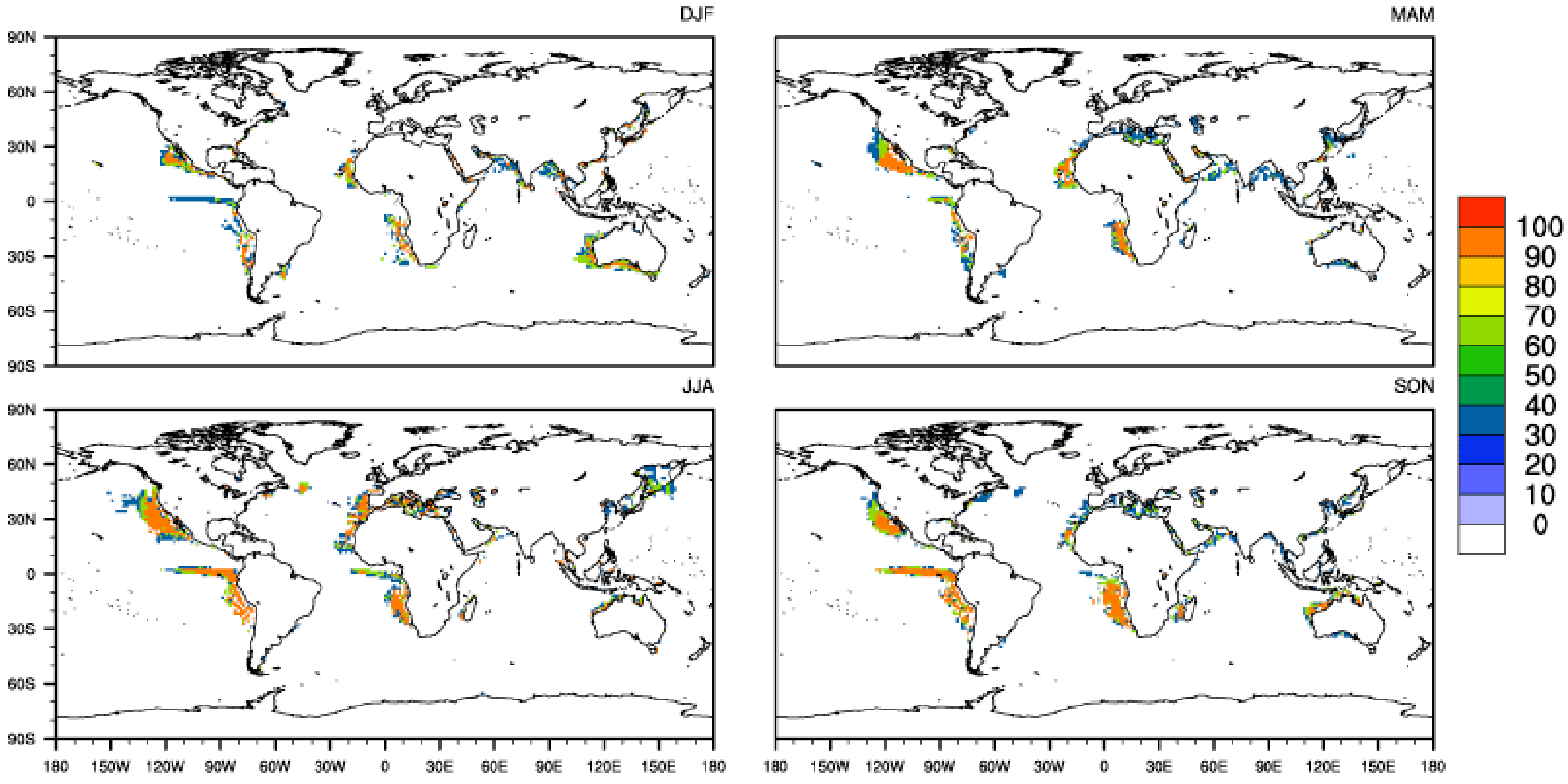
A closer look at the predicted stratocumulus climatology



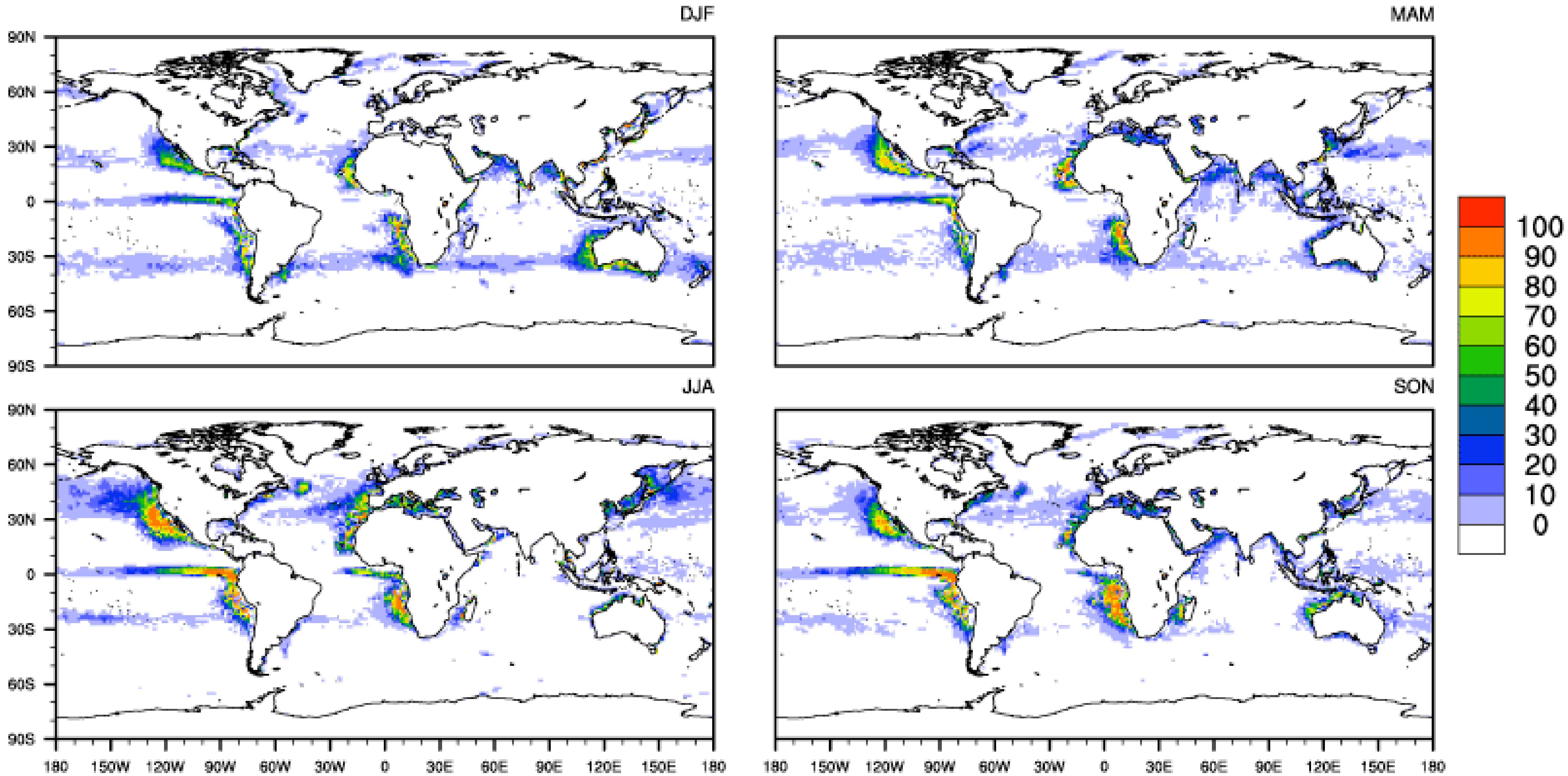
Seasonal Cloud Fraction: ERA40 Climatology (1984 - 2001)

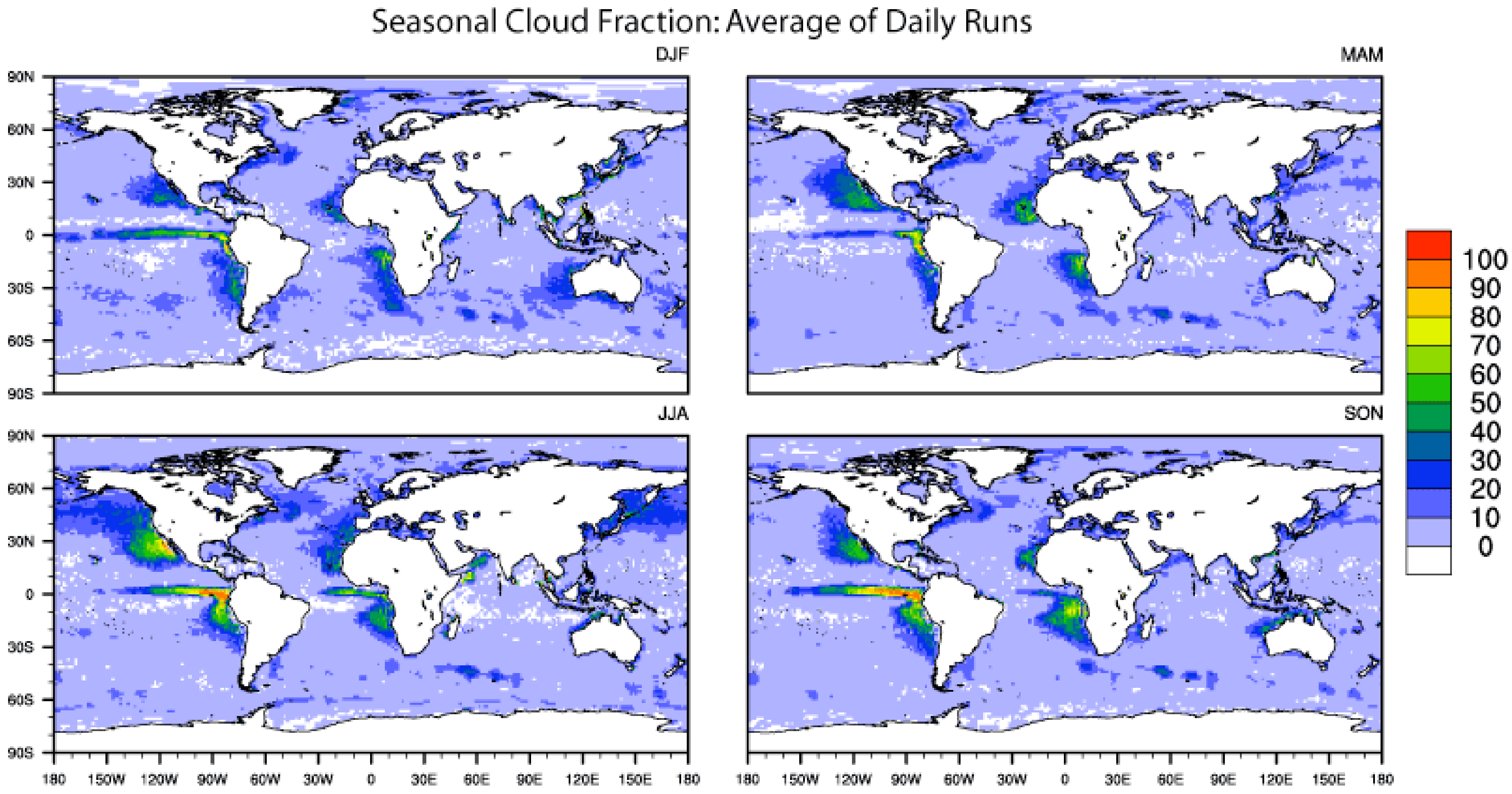


Seasonal Cloud Fraction: Climatology

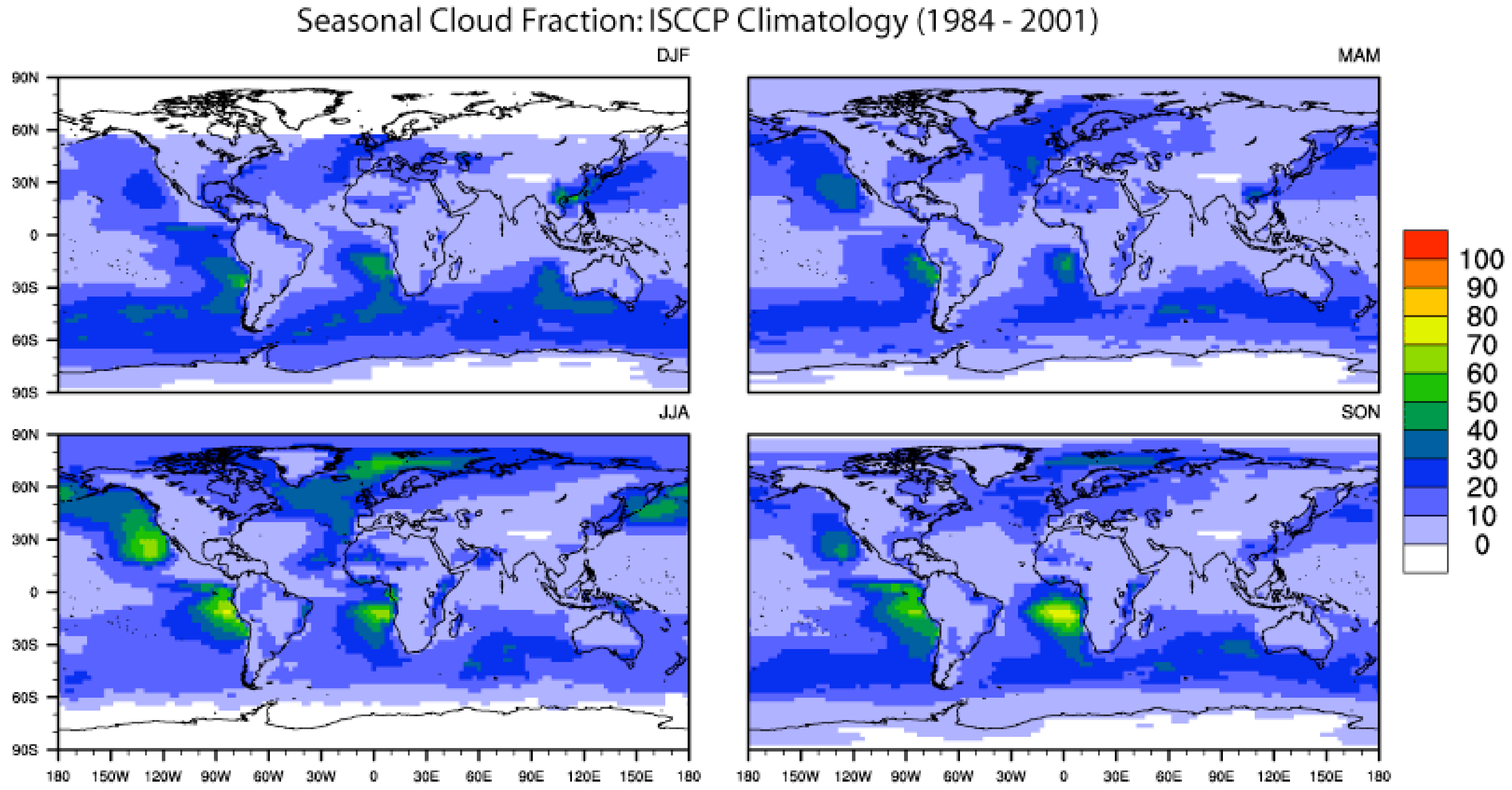


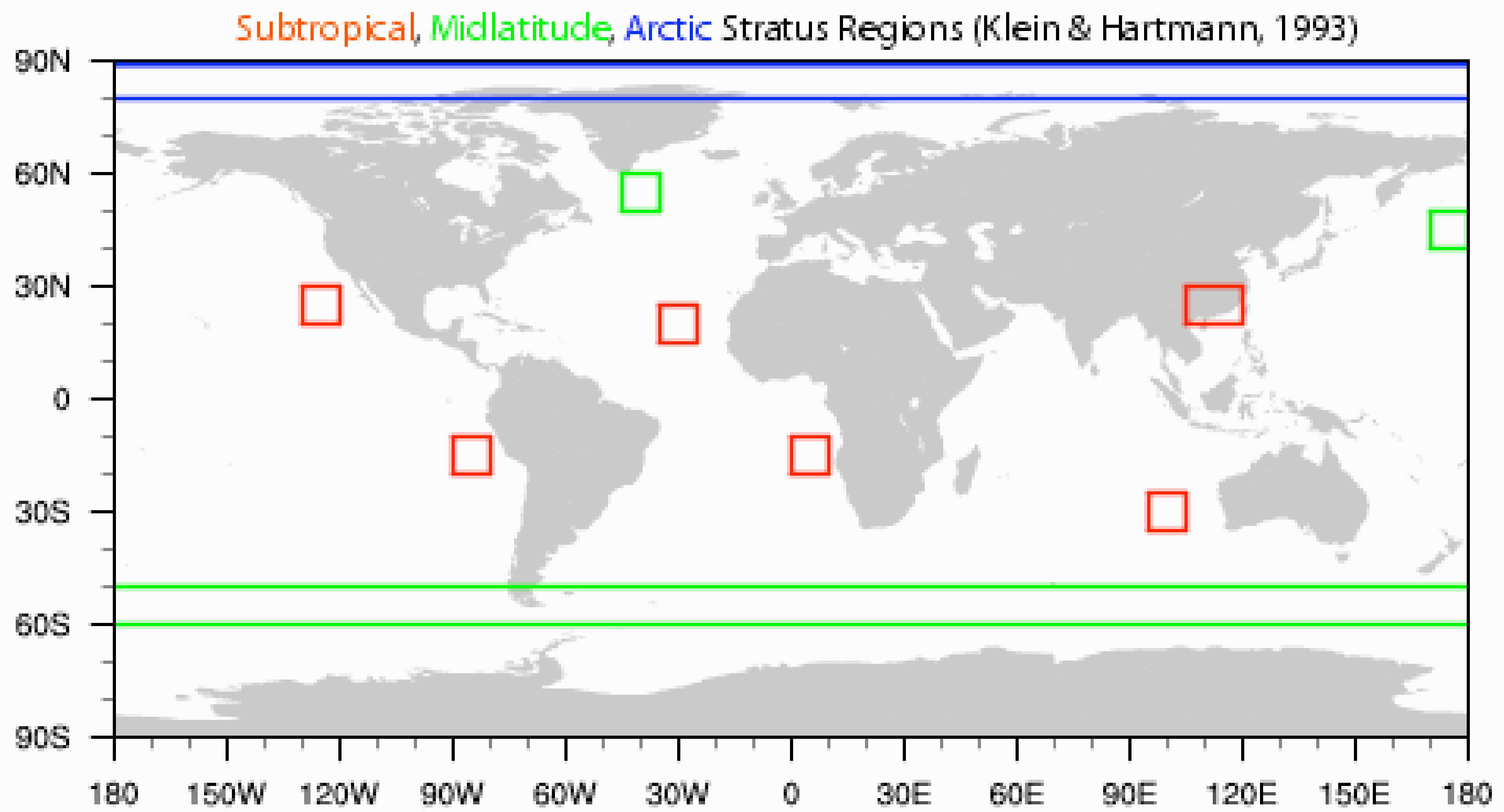
Seasonal Cloud Fraction: Average of Monthly Runs



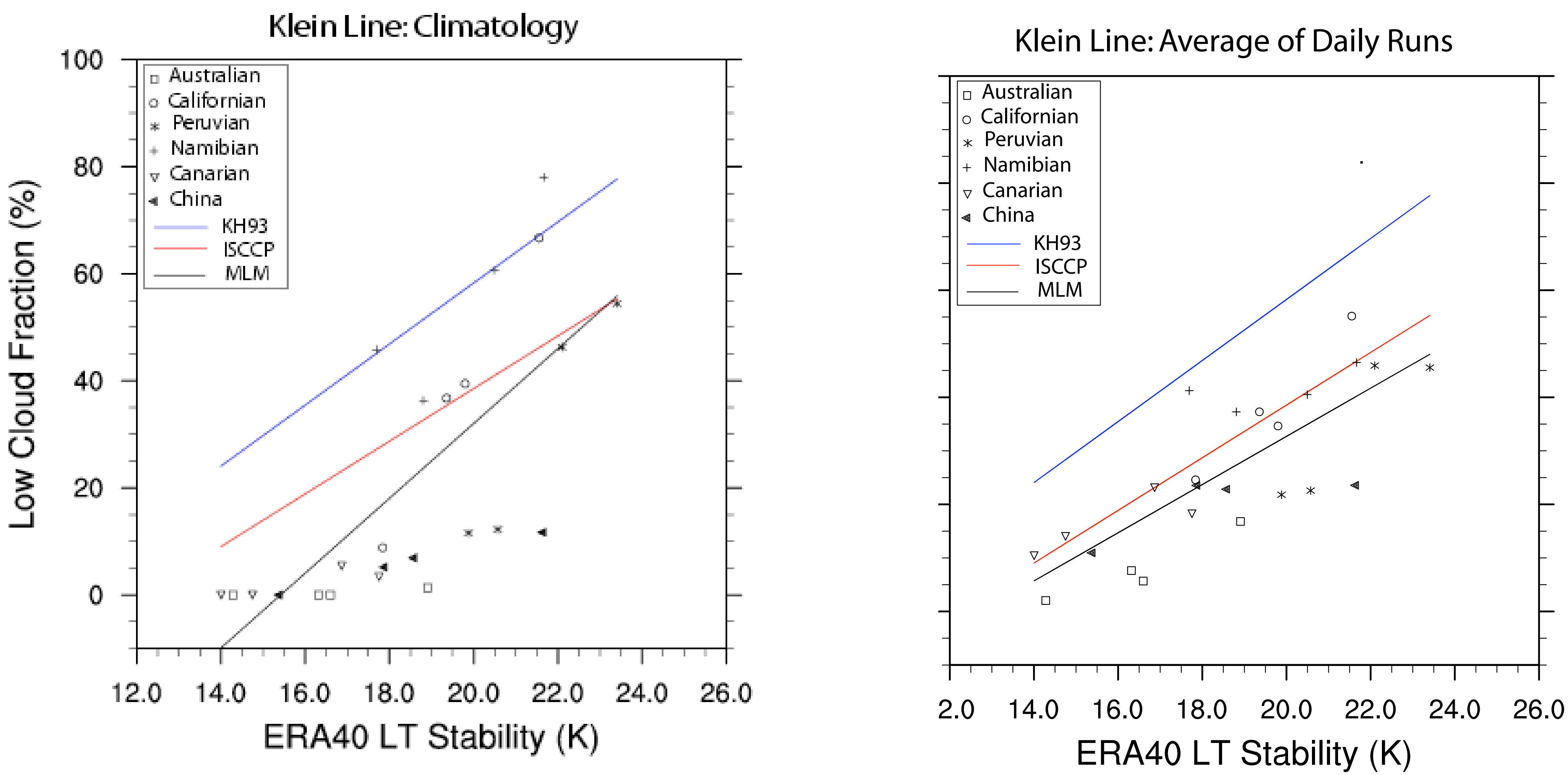


Seasonal Cloud Fraction: Average of Daily Runs
DJF
MAM
JJA
SON
90N
60N
30N
0
30S
60S
90S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
100
90
80
70
60
50
40
30
20
10
0

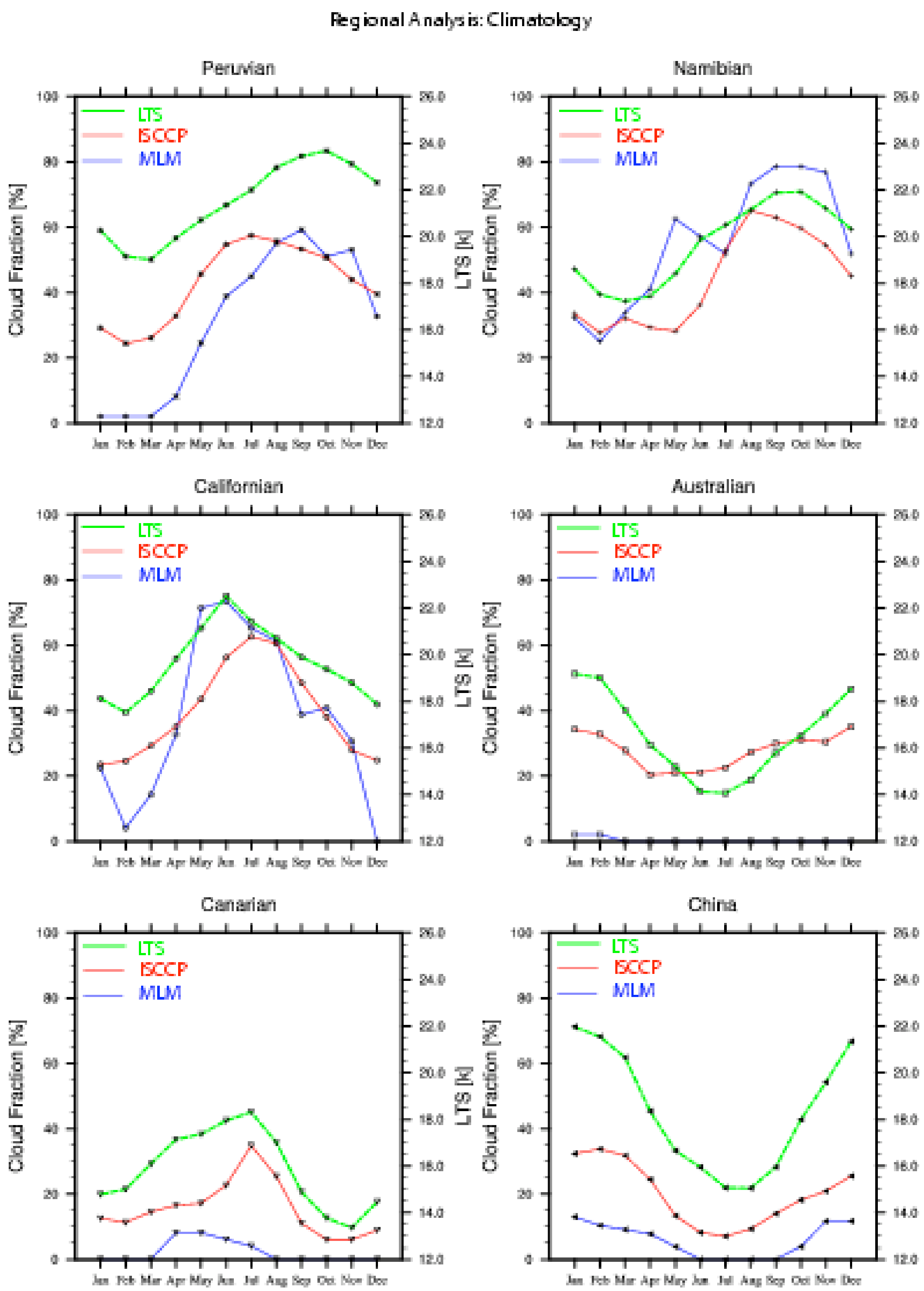

Seasonal Cloud Fraction: ISCCP Climatology (1984 - 2001)
DJF
MAM
JJA
SON
90N
60N
30N
0
30S
60S
90S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
100
90
80
70
60
50
40
30
20
10
0

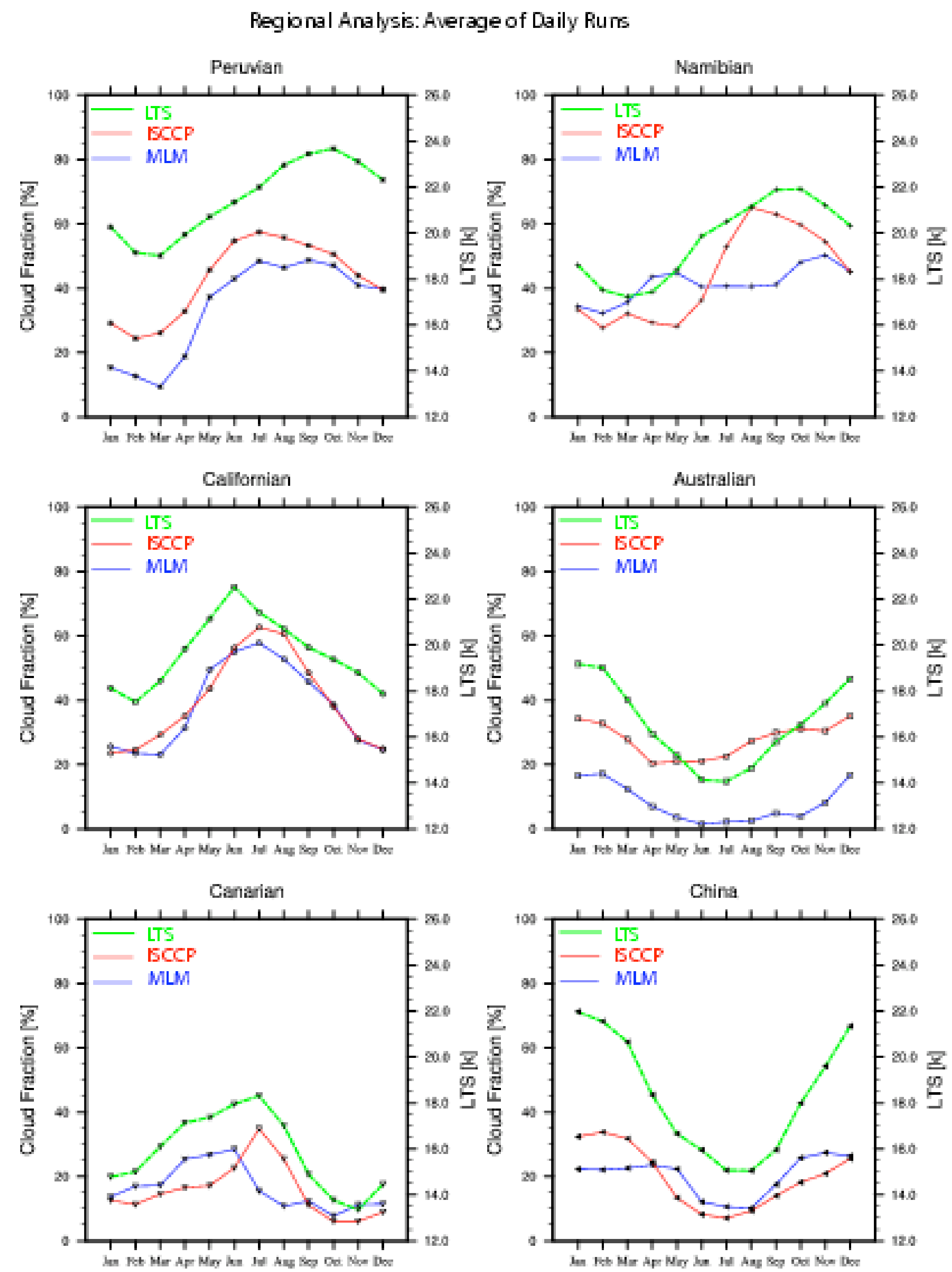


Subtropical, Midlatitude, Arctic Stratus Regions (Klein & Hartmann, 1993)
90N
60N
30N
0
30S
60S
90S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180



Klein Line: Climatology
100
80
60
40
20
0
Low Cloud Fraction (%)
Australian
Californian
Peruvian
Namibian
Canarian
China
KH93
ISCCP
MLM
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
ERA40 LT Stability (K)
Klein Line: Average of Daily Runs
Australian
Californian
Peruvian
Namibian
Canarian
China
KH93
ISCCP
MLM
2.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
ERA40 LT Stability (K)


Regional Analysis: Climatology
Peruvian
Namibian
Californian
Australian
Canarian
China
LTS
ISCCP
MLM
Cloud Fraction [%]
LTS [K]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Regional Analysis: Average of Daily Runs
Peruvian
Namibian
Californian
Australian
Canarian
China
LTS
ISCCP
MLM
Cloud Fraction [%]
LTS [K]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Remarks

- Bulk framework provides a unified basis for describing boundary layer processes.
- Modest simplifications often render model's behavior analytically tractable. Some surprising results appear naturally, for instance the cloud fraction in the trades begin near 10%.
- Can be used to explore climatological data sets, i.e., a priori tests.
- Explorations of stratocumulus climatology promising, thus providing a basis for better understanding factors responsible for the regulation of this climatologically important cloud regime.
- Basis for parameterization? For instance, by relaxation to the equlibria?