Have the number and intensity of tropical cyclones increased?

William M. Briggs

wmbriggs.com

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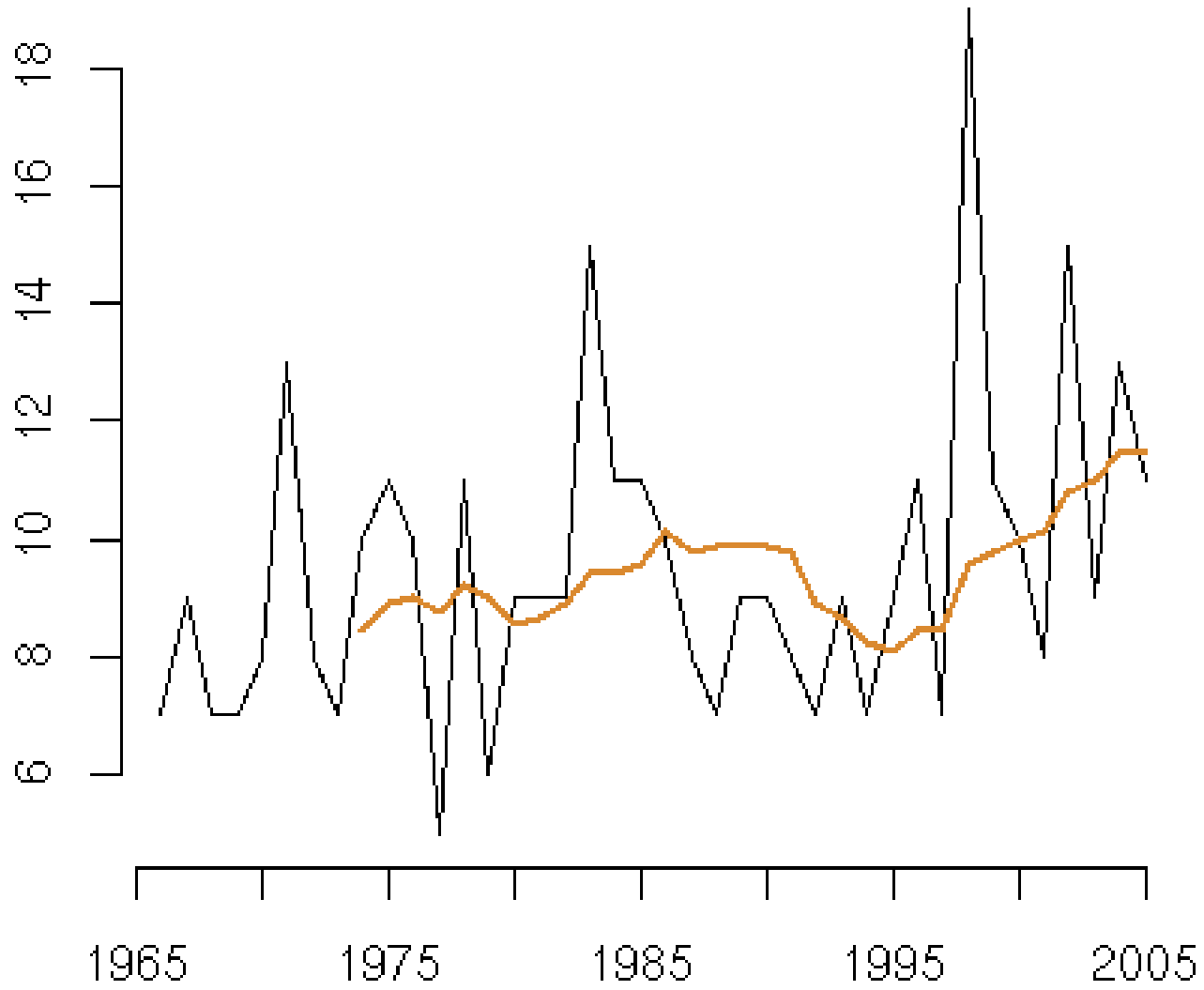
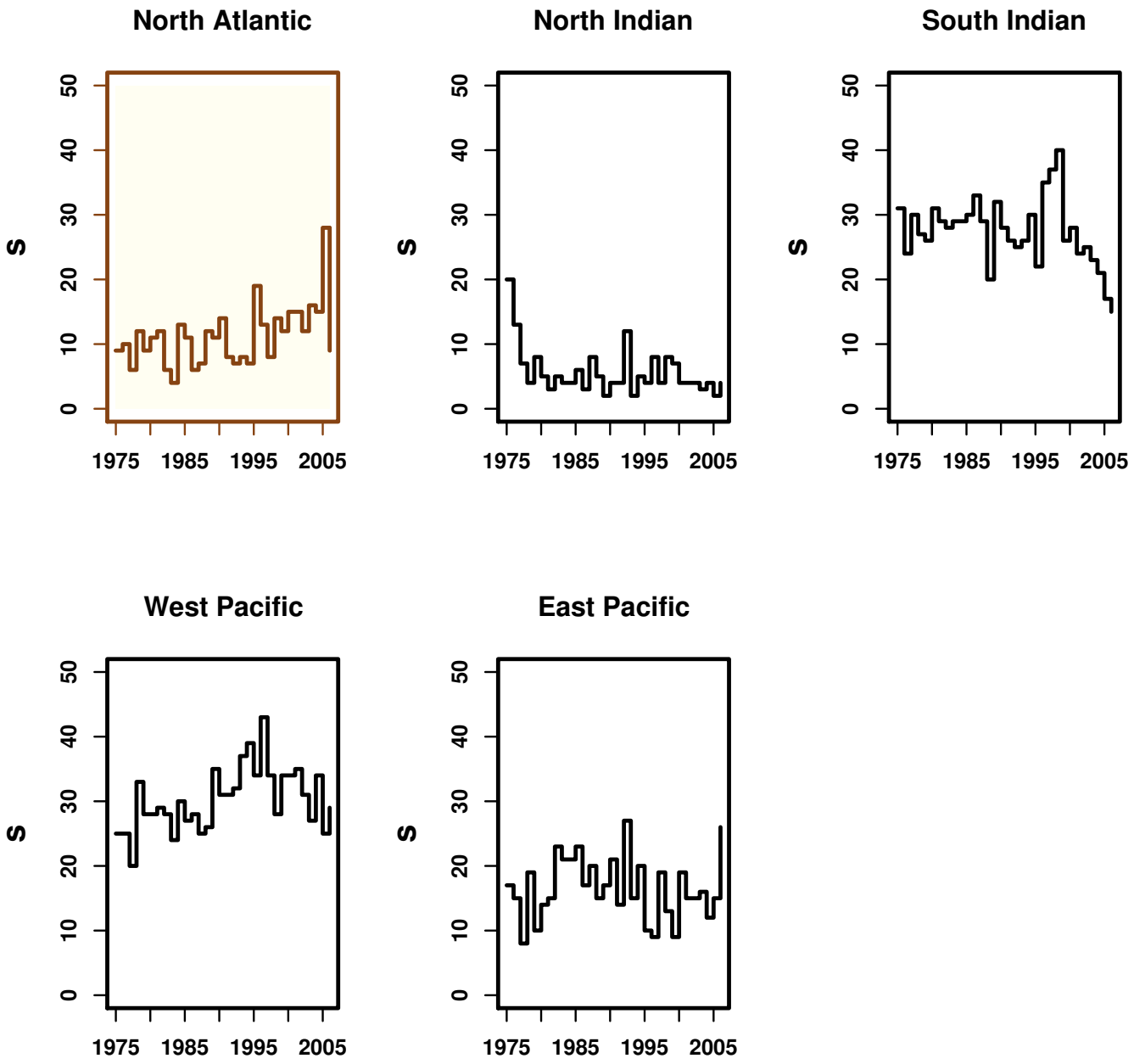
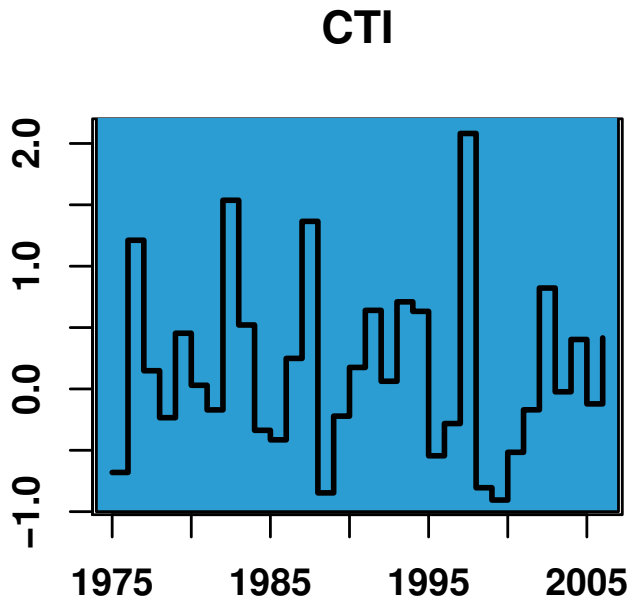
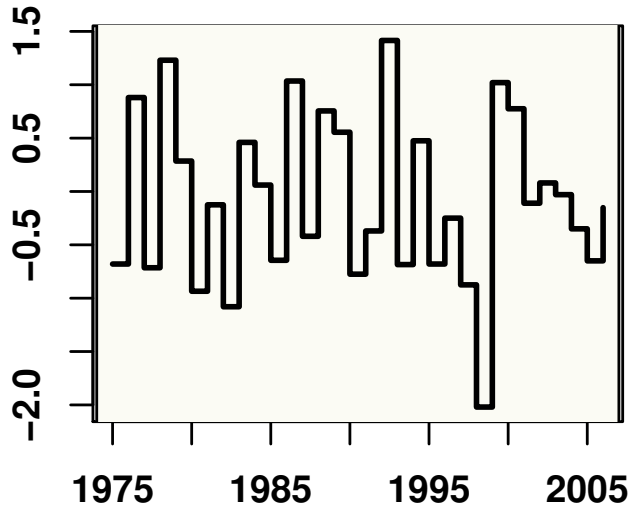
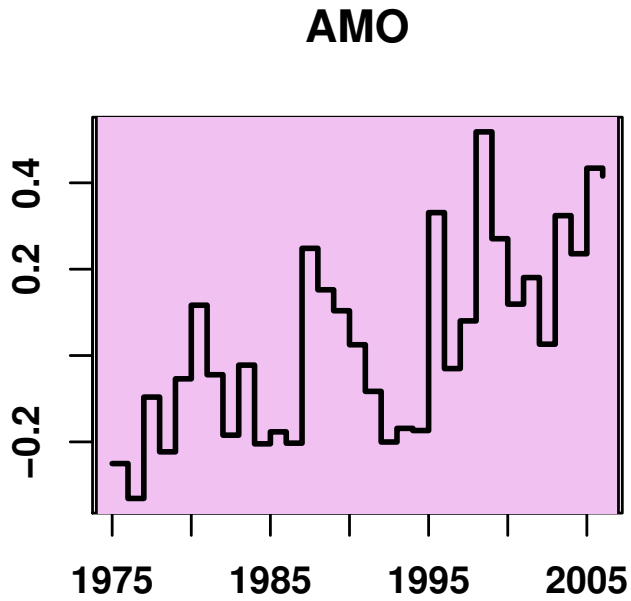

6
8
10
12
14
16
18
1965
1975
1985
1995
2005

What	Method
5 oceans	Best Track (`unisys.com`)
s	Count of all storms that lasted at least 6 hours*.
m	Number of days each storm lived.
V_{max}	Raw wind speed for each 6-hour obs.
$track$	Summed great circle distances over m.
PDI	$\approx \sum_0^m V_{\text{max}}^3$: power dissipation index


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
S
0
10
20
30
40
50
1975
1985
1995
2005


CTI
2.0
1.0
0.0
−1.0
1975
1985
1995
2005

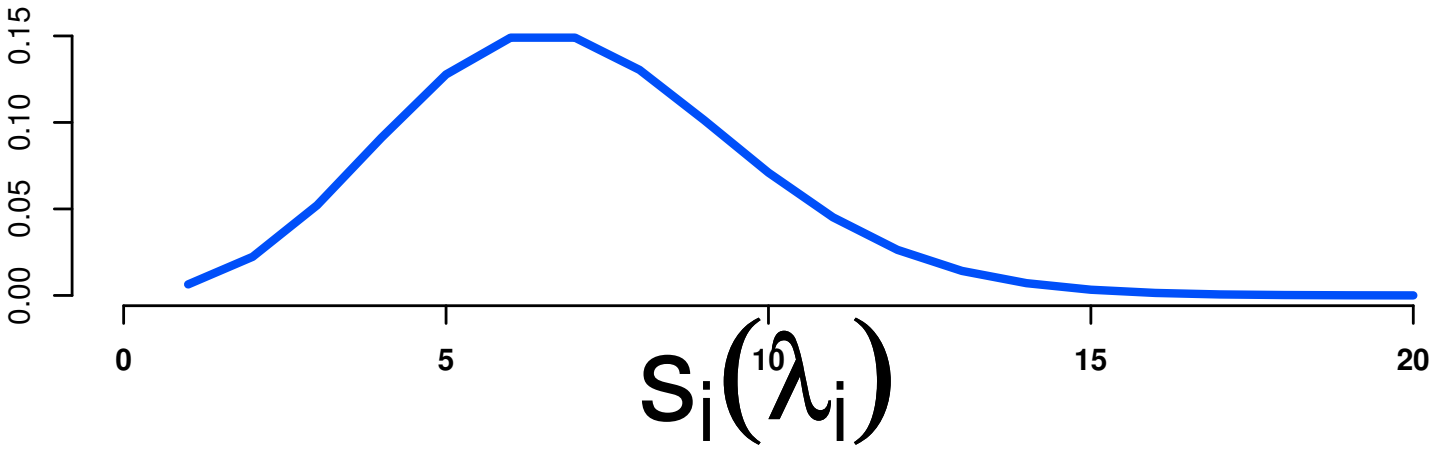

NAOI
1.5
0.5
−0.5
−2.0
1975
1985
1995
2005


AMO
0.4
0.2
−0.2
1975
1985
1995
2005

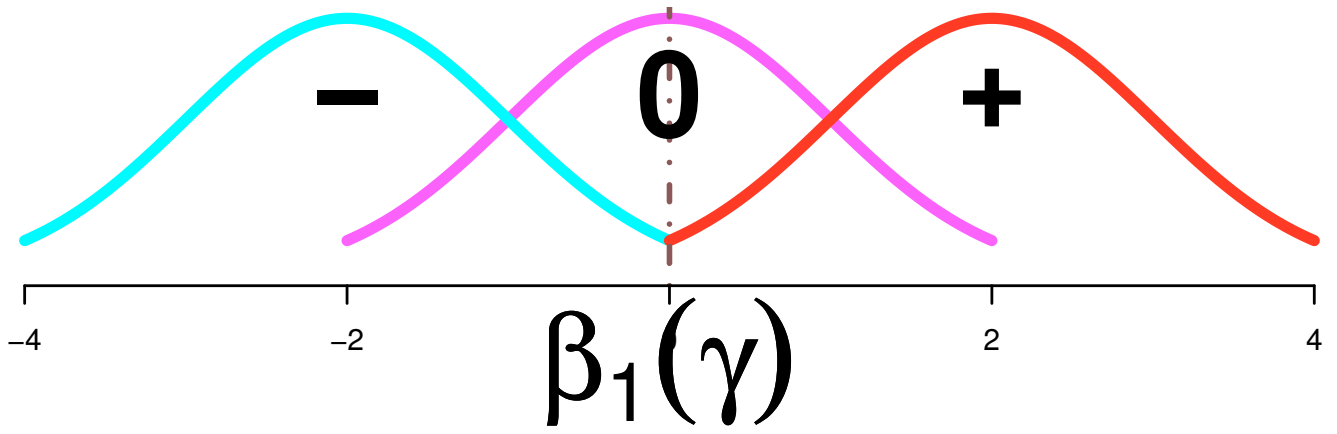
$$
\begin{aligned}
s_{ij} &\sim \text{Poisson}(\lambda_{ij}),\ \ i = 1 \ldots 5,\ \ j = 1 \ldots n \\
\log(\lambda_{ij}) &= \beta^s_{0i} + \beta^s_{1i} t_j + \beta^s_{2i} \text{CTI}_j + \beta^s_{3i} \text{NAOI}_j \\
&\quad + \beta^s_{4i} \text{AMO}_j
\end{aligned}
$$

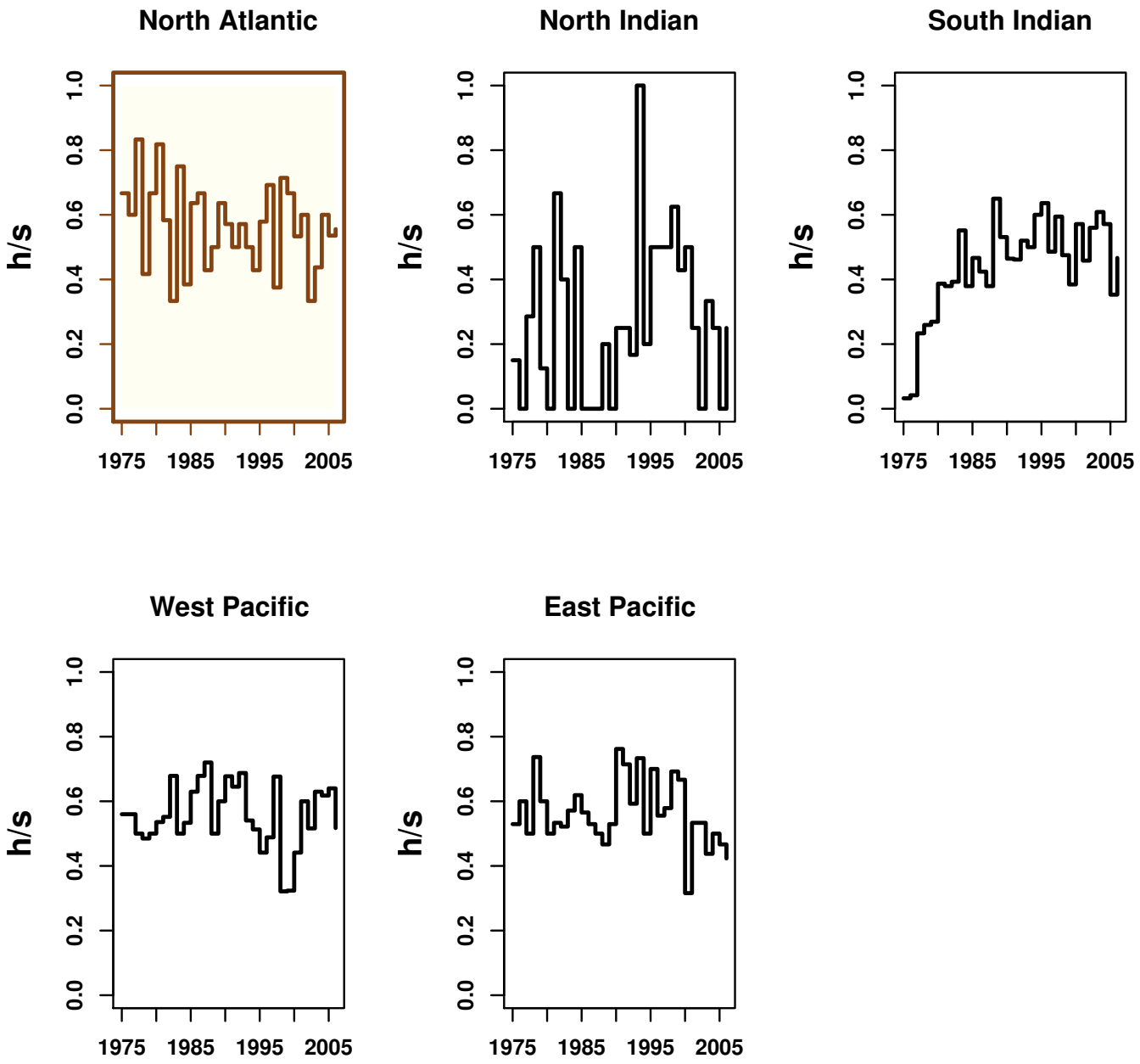
$$
\begin{aligned}
\beta^s_{ki} | \gamma^s_k, \tau^s_k &\sim \text{N}(\gamma^s_k, \tau^s_k),\quad k = 0, 1, 2, 3, 4 \\
\gamma^s_k &\sim \text{N}(0, 1e-6) \\
\tau^s_k &\sim \text{Gamma}(.001, .001)
\end{aligned}
$$

interest in γ^s_1, β^s_{1i}



$$\log(\lambda_i) = \beta_{0i} + \beta_{1i}t + \cdots$$



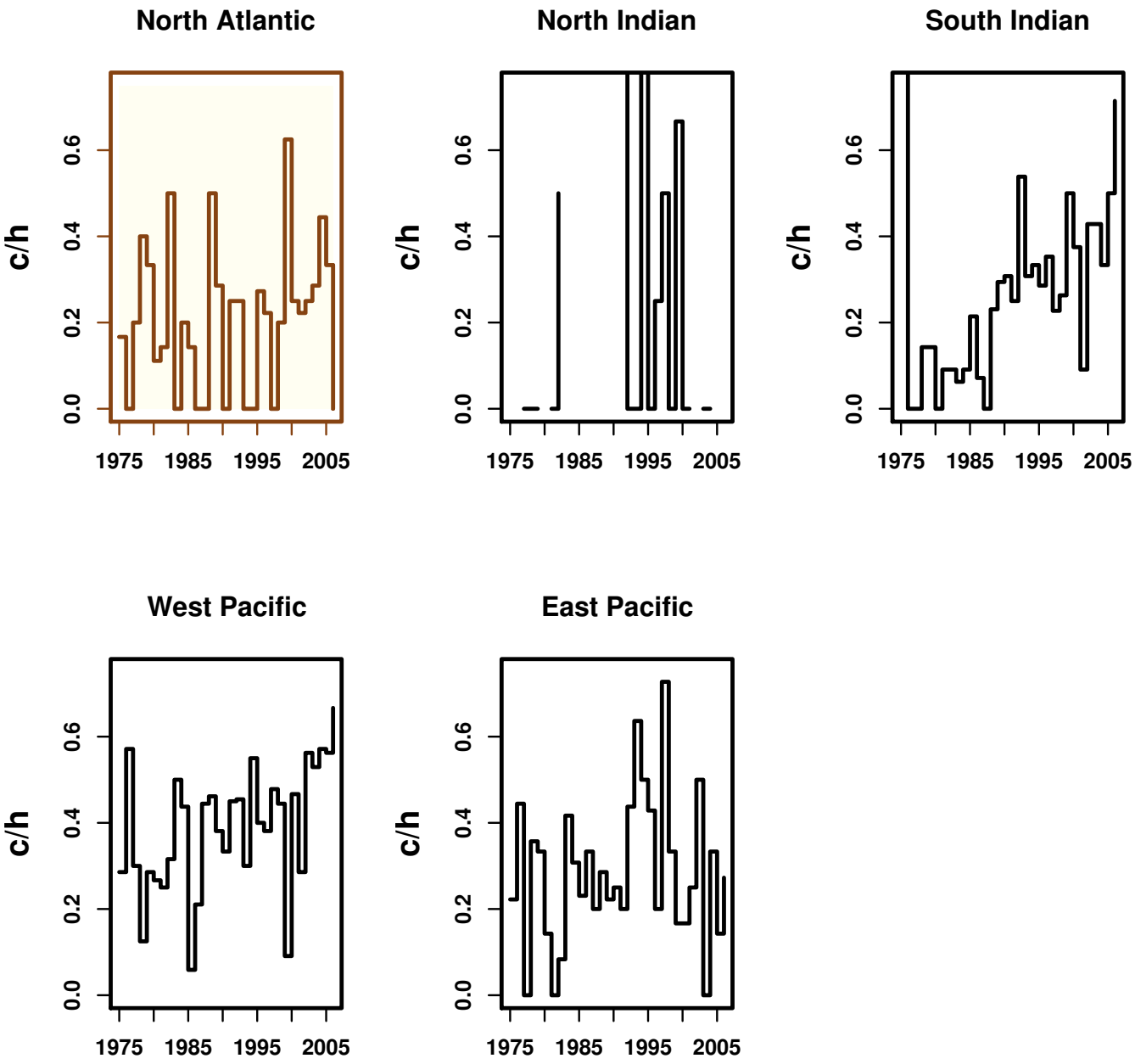

North Atlantic
North Indian
South Indian
West Pacific
East Pacific
h/s
0.0
0.2
0.4
0.6
0.8
1.0
1975
1985
1995
2005

$$
\begin{aligned}
h_{ij}|s_{ij},\theta_{ij} &\sim \text{Binomial}(s_{ij},\theta_{ij}) \\
\text{logit}(\theta_{ij}) &= \beta^h_{0i} + \beta^h_{1i} t_j + \beta^h_{2i}\text{CTI}_j + \beta^h_{3i}\text{NAOI}_j \\
&\quad + \beta^h_{4i}\text{AMO}_j
\end{aligned}
$$

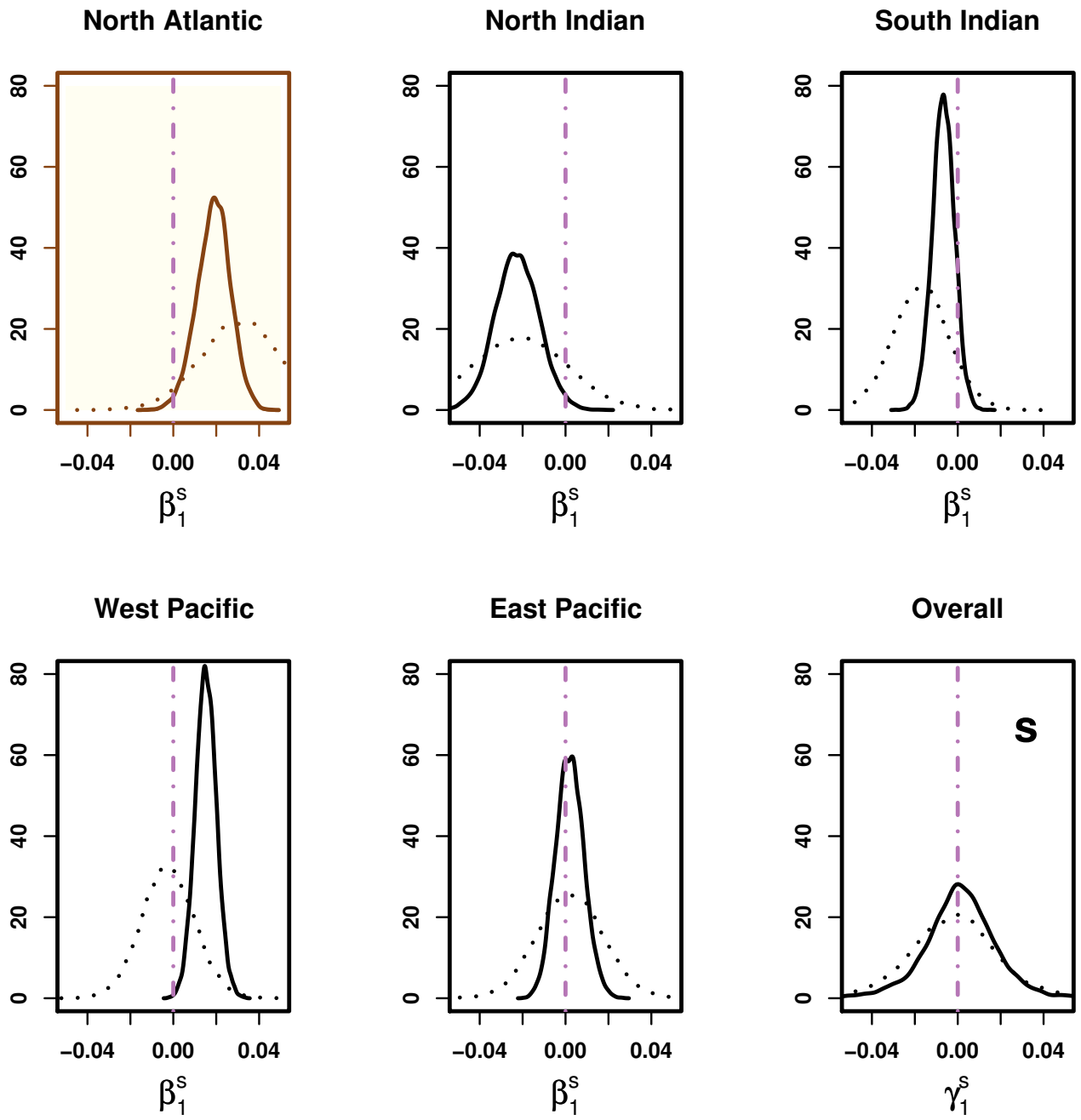
$$
\beta^h_{jk}|\gamma^h_k,\tau^h_k \sim \text{N}(\gamma^h_k,\tau^h_k),\ \ k = 0,\ldots,4
$$

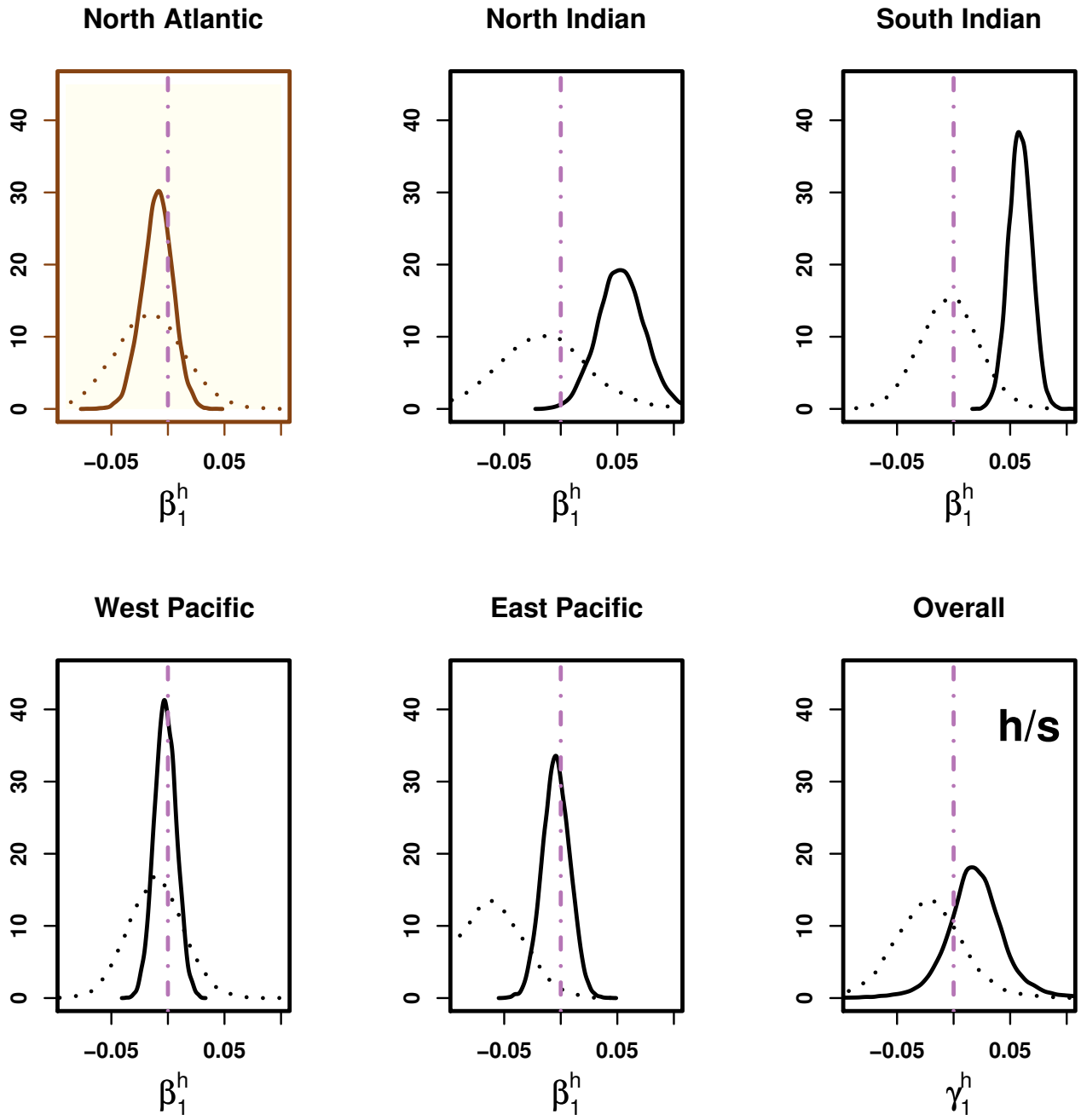
$$
\begin{aligned}
\gamma^h_k &\sim \text{N}(0, 1.0E-6) \\
\tau^h_k &\sim \text{Gamma}(.001,.001)
\end{aligned}
$$

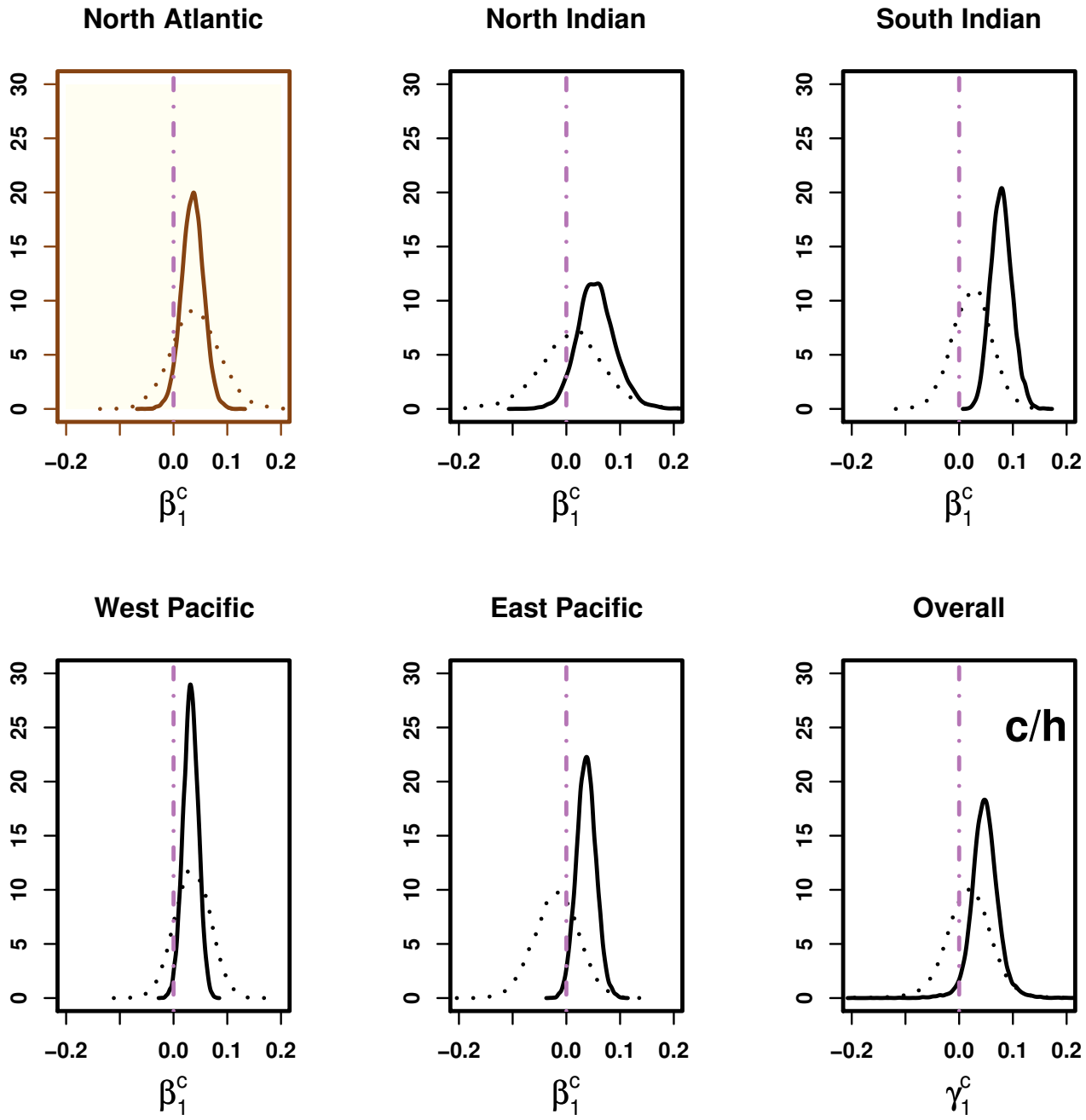
interest in γ^h_1, β^h_{1i}


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
c/h
0.0
0.2
0.4
0.6
1975
1985
1995
2005

$$
\begin{aligned}
c_{ij}|h_{ij},\theta_{ij} &\sim \text{Binomial}(h_{ij},\xi_{ij}) \\
\text{logit}(\xi_{ij}) &= \beta^c_{0i} + \beta^c_{1i}t_j + \beta^c_{2i}\text{CTI}_j + \beta^c_{3i}\text{NAOI}_j \\
&\quad +\beta^c_{4i}\text{AMO}_j \\
\\
\beta^c_{jk}|\gamma^c_k,\tau^c_k &\sim \text{N}(\gamma^c_k,\tau^c_k),\ \ k=0,\ldots,4 \\
\\
\gamma^c_k &\sim \text{N}(0,1.0E-6) \\
\tau^c_k &\sim \text{Gamma}(.001,.001) \\
\\
&\quad \text{interest in } \gamma^c_1,\beta^c_{1i}
\end{aligned}
$$


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Overall
S
0
20
40
60
80
−0.04
0.00
0.04
β_1^s
γ_1^s


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Overall
h/s
0
10
20
30
40
−0.05
0.05
β_1^h
γ_1^h


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Overall
c/h
0
5
10
15
20
25
30
−0.2
0.0
0.1
0.2
β_1^c
γ_1^c

Effect of CTI/NAOI/AMO on s

Ocean	2.5%	50%	97.5%
	β_2^s: CTI		
NA	**-0.36**	**-0.18**	**-0.03**
	β_3^s: NAOI		
	none		
	β_4^s: AMO		
	none		

Effect of CTI/NAOI/AMO on $\mathbf{h/s}$

Ocean	2.5%	50%	97.5%
	β_2^h: CTI		
WP	**0.01**	**0.21**	**0.42**
	β_3^h: NAOI		
	none		
	β_4^h: AMO		
	none		

Effect of CTI/NAOI/AMO on $\mathbf{c/h}$

Ocean	2.5%	50%	97.5%
	β_2^c: CTI		
WP	**0.06**	**0.32**	**0.59**
EP	**0.03**	**0.38**	**0.74**
	β_3^c: NAOI*		
NA	**0.04**	**0.26**	**0.53**
SI	**0.06**	**0.26**	**0.47**
WP	**0.00**	**0.21**	**0.40**
EP	**0.03**	**0.25**	**0.48**
Overall	**0.05**	**0.25**	**0.46**
	β_4^c: AMO		
	none		

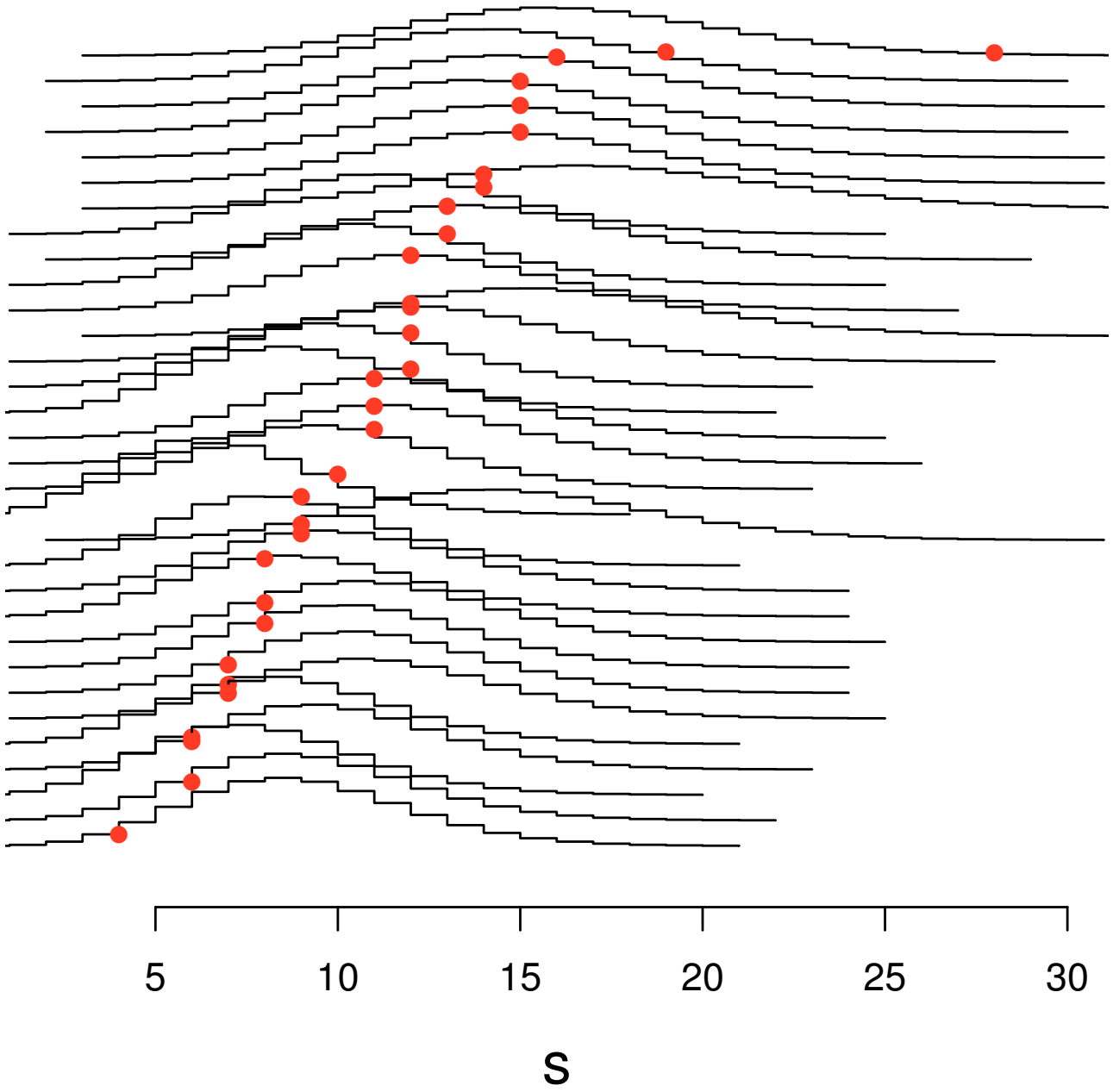
*Without AMO

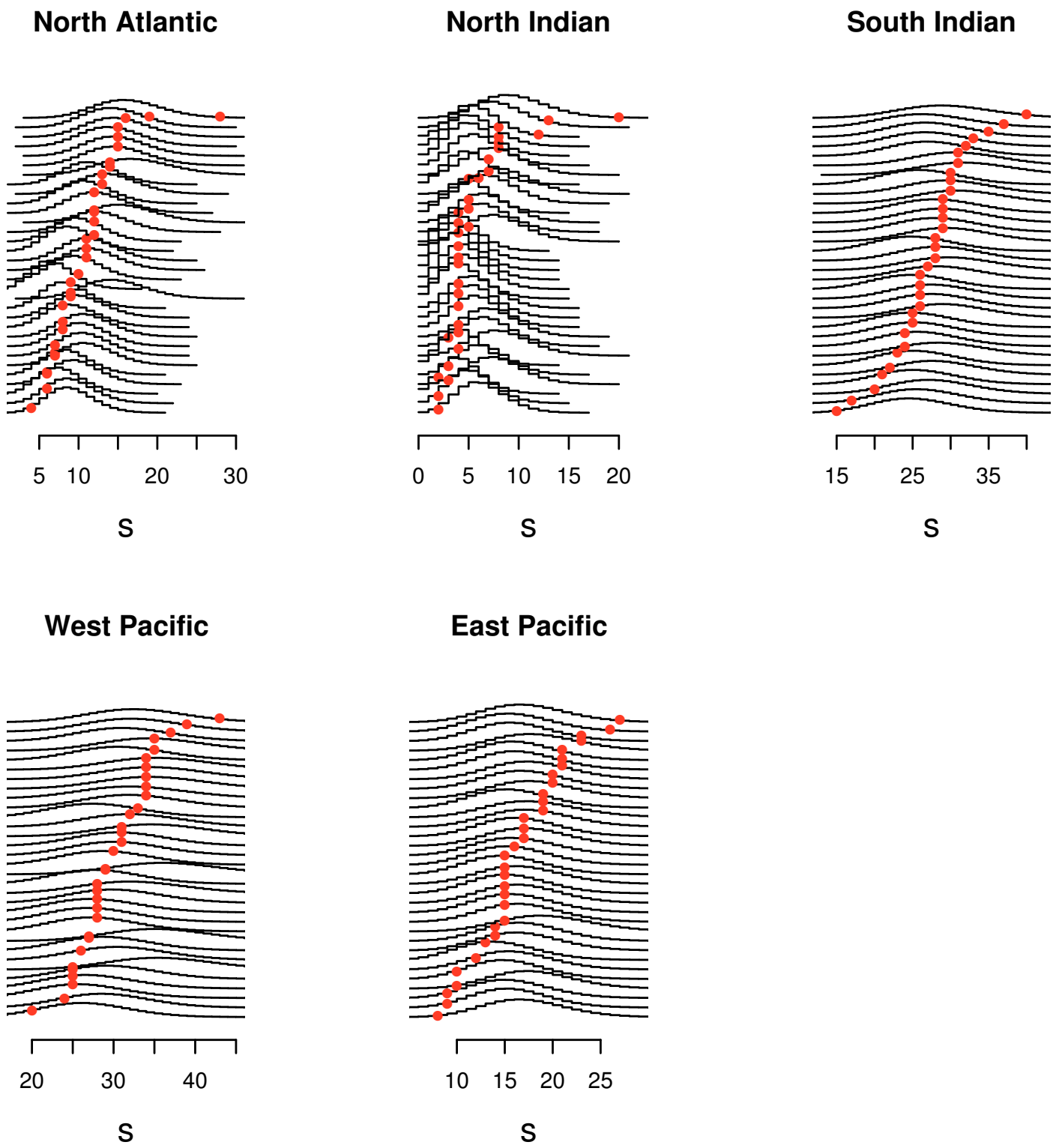
New verification method!

$$p(\lambda_{ij}|\text{data}) = \int_{-\infty}^{\infty} p(\lambda_{ij}|\beta, \text{data}) p(\beta|\text{data}) d\beta$$

$$p(s_{ij}|\text{data}) = \int_{0}^{\infty} p(s_{ij}|\lambda_{ij}, \text{data}) \times p(\lambda_{ij}|\text{data}) d\lambda_{ij}$$

Verification plot $\longrightarrow$ CRPS $\longrightarrow$ Skill score


North Atlantic
5
10
15
20
25
30
S


North Atlantic
5 10 20 30
S
North Indian
0 5 10 15 20
S
South Indian
15 25 35
S
West Pacific
20 30 40
S
East Pacific
10 15 20 25
S

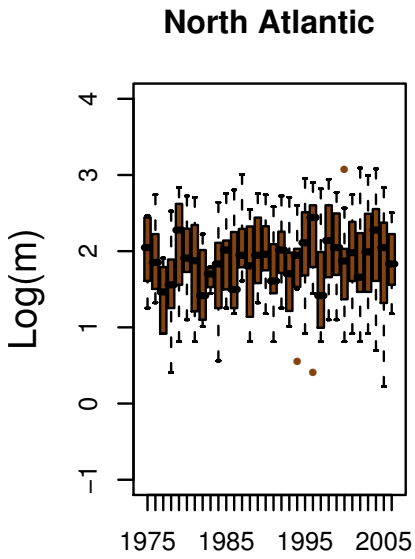
3-D Intensity:

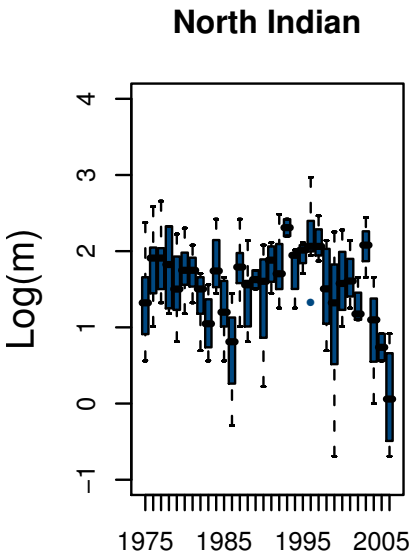
1. Storm days m (nearest 6 hours)

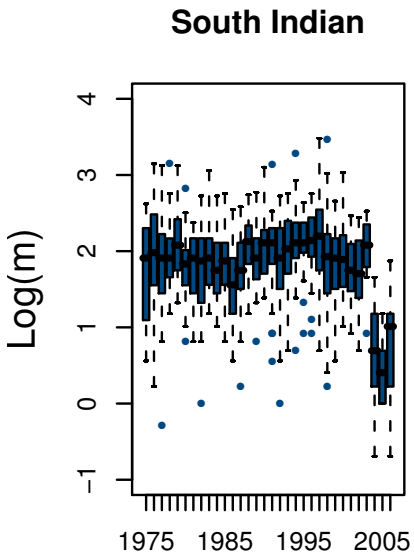
2. Track length (km)

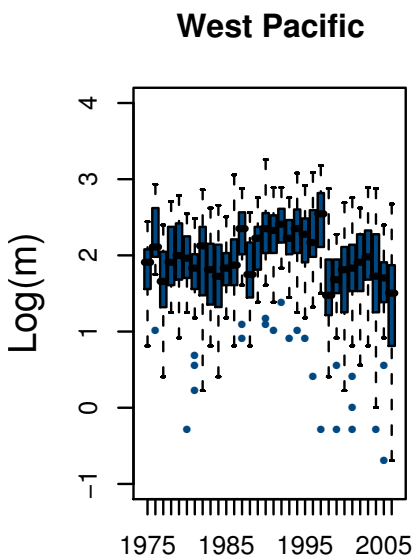
3. Power Dissipation Index (PDI)

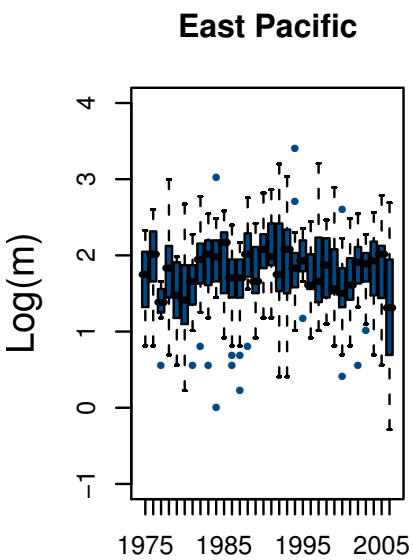
$$\int_0^m V_{\text{max}}^3 dt \propto \sum \left(\frac{V_{\text{max}}}{100} \right)^3$$


North Atlantic
Log(m)
−1
0
1
2
3
4
1975
1985
1995
2005

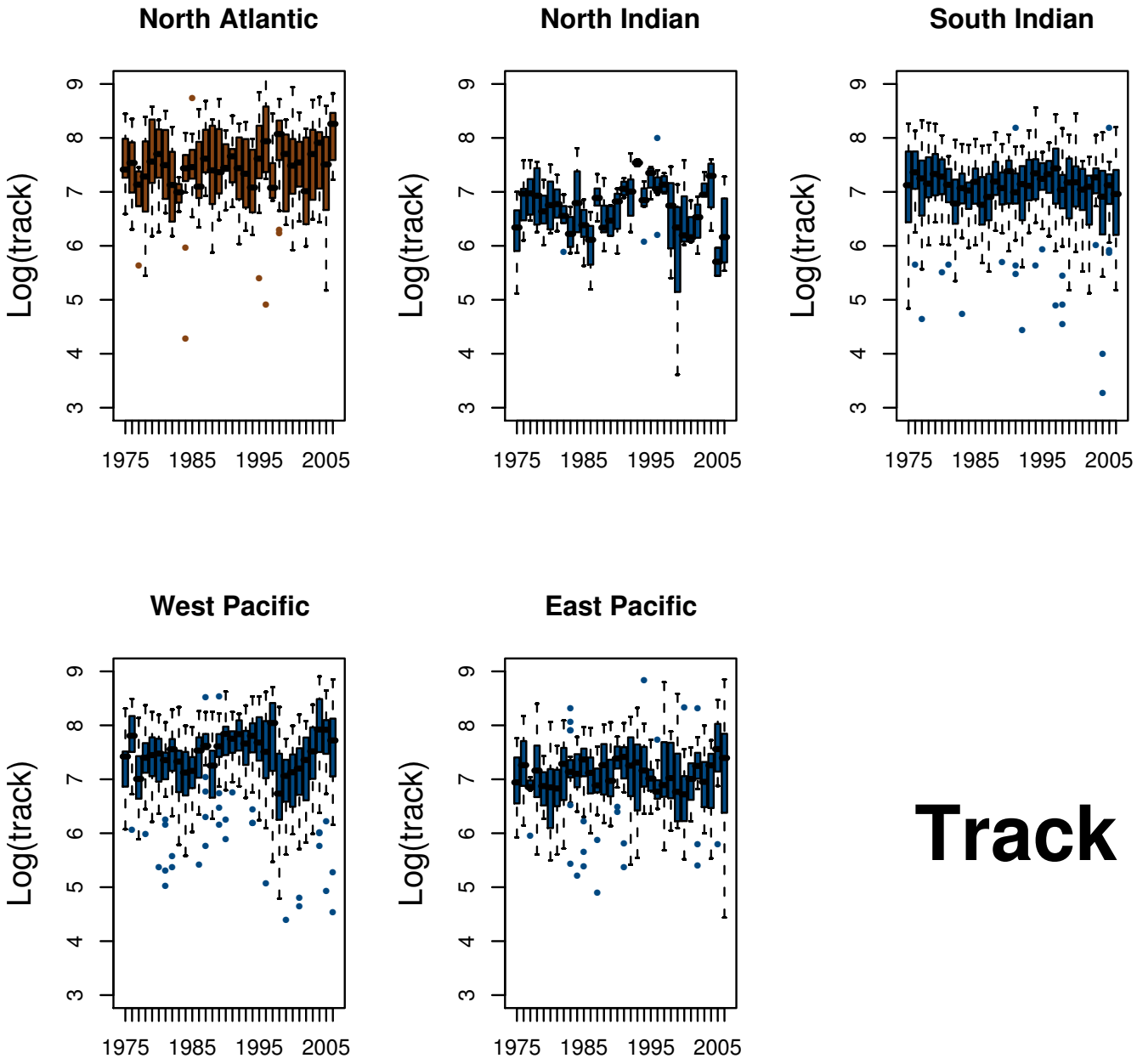

North Indian
Log(m)
−1
0
1
2
3
4
1975
1985
1995
2005

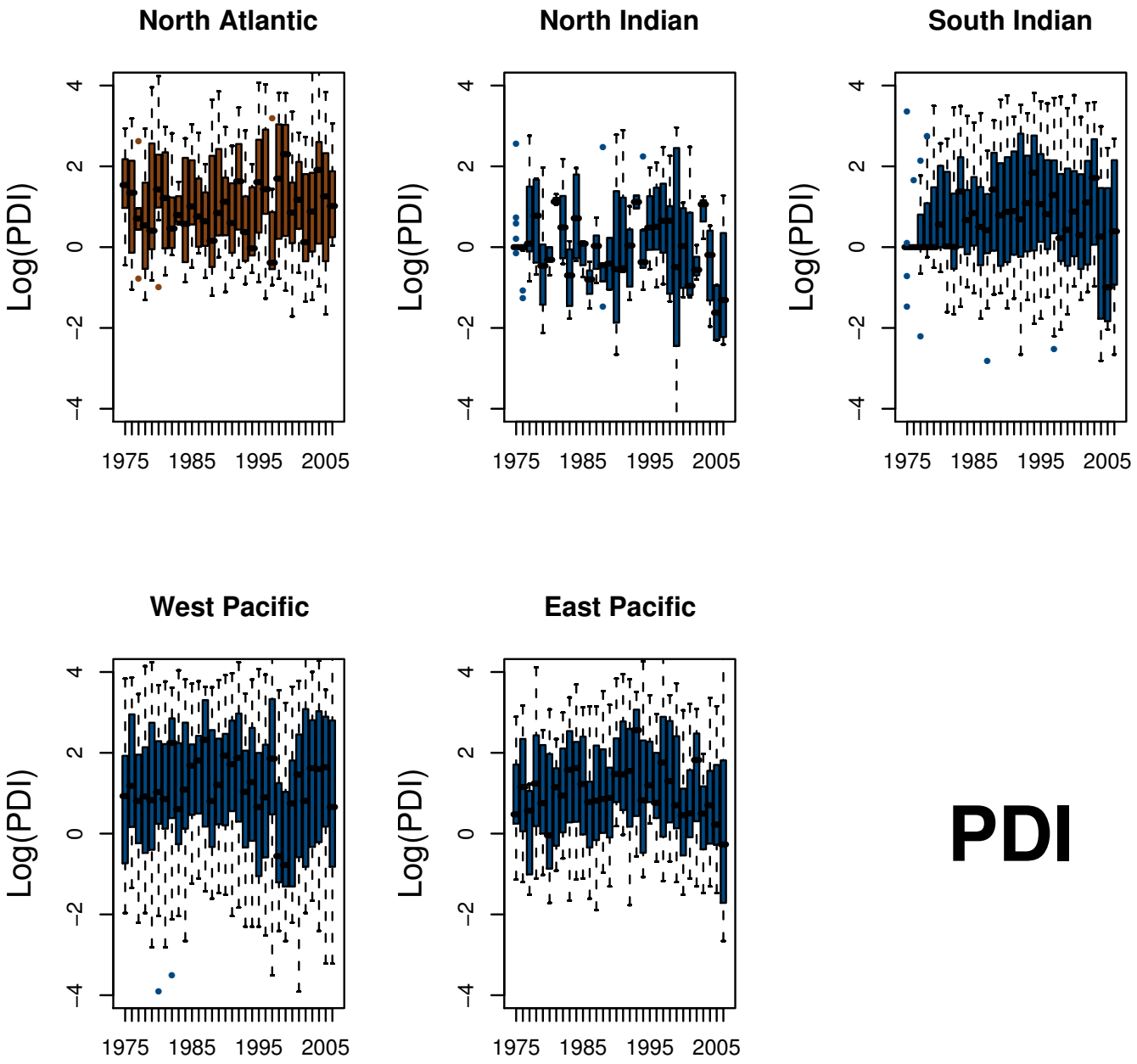

South Indian
Log(m)
−1
0
1
2
3
4
1975
1985
1995
2005


West Pacific
Log(m)
−1
0
1
2
3
4
1975
1985
1995
2005


East Pacific
Log(m)
−1
0
1
2
3
4
1975
1985
1995
2005

Storm Days


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Log(track)
3
4
5
6
7
8
9
1975
1985
1995
2005
Track


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Log(PDI)
4
2
0
−2
−4
1975
1985
1995
2005
PDI

$$y_{ijk} = \begin{pmatrix} \log(m) \\ \log(\text{track}) \\ \log(\text{PDI}) \end{pmatrix}_{ijk}$$

$$y_{ijk1} = \log(m)_{ijk} \quad \text{etc.}$$

$$y_{ijk} \sim \text{MVN}(\mu_{ijk}, \Lambda_{ij})$$

$$
\begin{aligned}
\mu_{ijkl} &= \beta^z_{0il} + \beta^z_{1il} t_j + \beta^z_{2il} \mathsf{CTI}_j + \beta^z_{3il} \mathsf{NAOI}_j \\
&\quad + \beta^z_{4il} \mathsf{AMO}_j \\
&\quad l = 1 \ldots 3, k = 1 \ldots s_{ij} \\
\beta^z_{ril} &\sim \mathsf{N}(\pi_{rl}, \phi_{rl}), \quad r = 0, 1, 2, 3 \\
\\
\pi_{rl} &\sim \mathsf{N}(a_{rl}, b_{rl}) \\
a_{rl} &\sim \mathsf{N}(0, 1e-6) \\
b_{rl} &\sim \mathsf{Gamma}(0.001, 0.001) \\
\\
\phi_{rl} &\sim \mathsf{Gamma}(0.001, 0.001)
\end{aligned}
$$

Prior 1

$$\Lambda_{ij} \sim \text{Wishart}(\mathbf{I}_{ij}, 3)$$

Prior 2

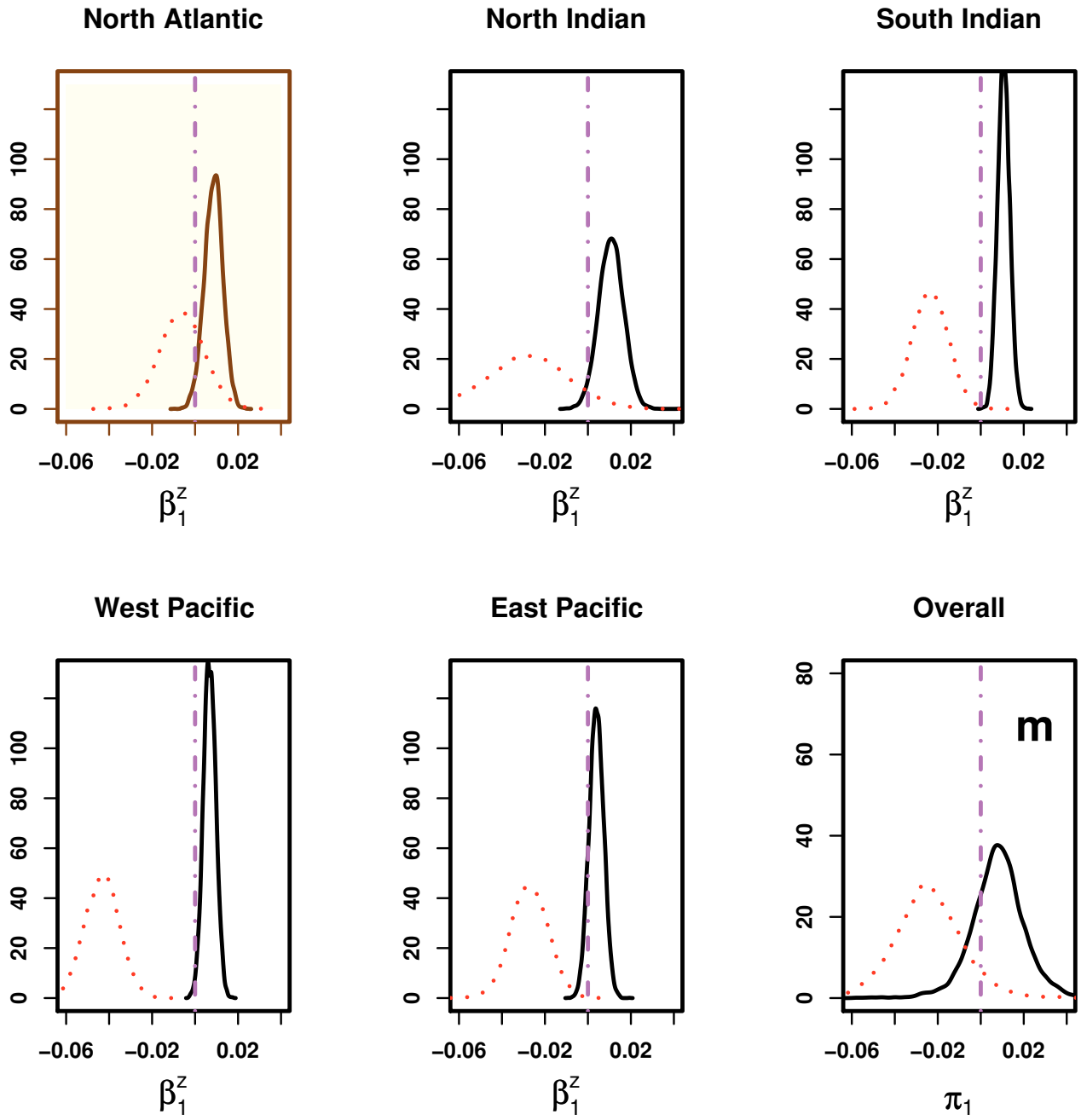
$$\Lambda_{ij} \sim \text{Wishart}(f(\mathbf{I}_{ij}, t), 3)$$

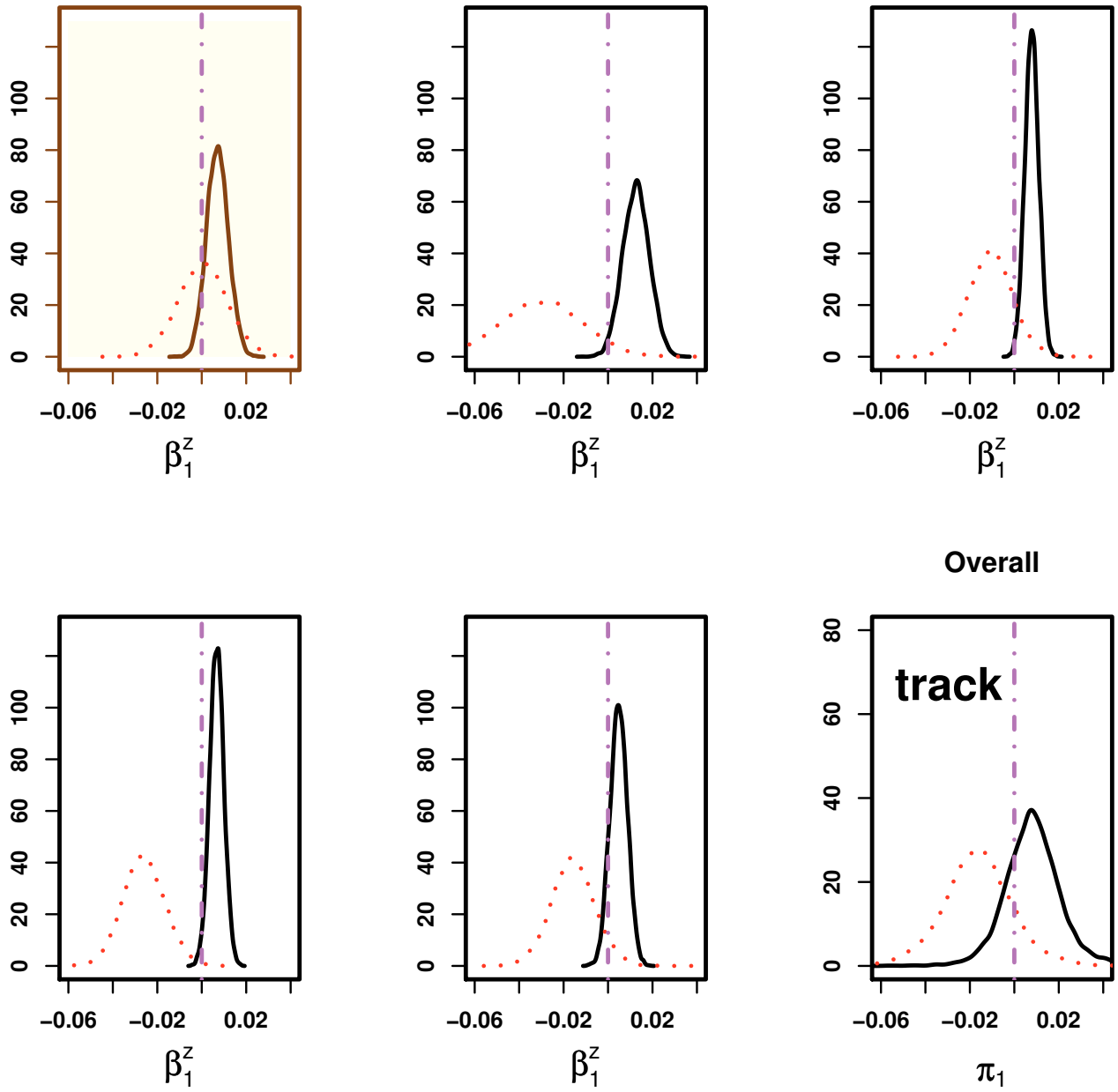
Prior 2

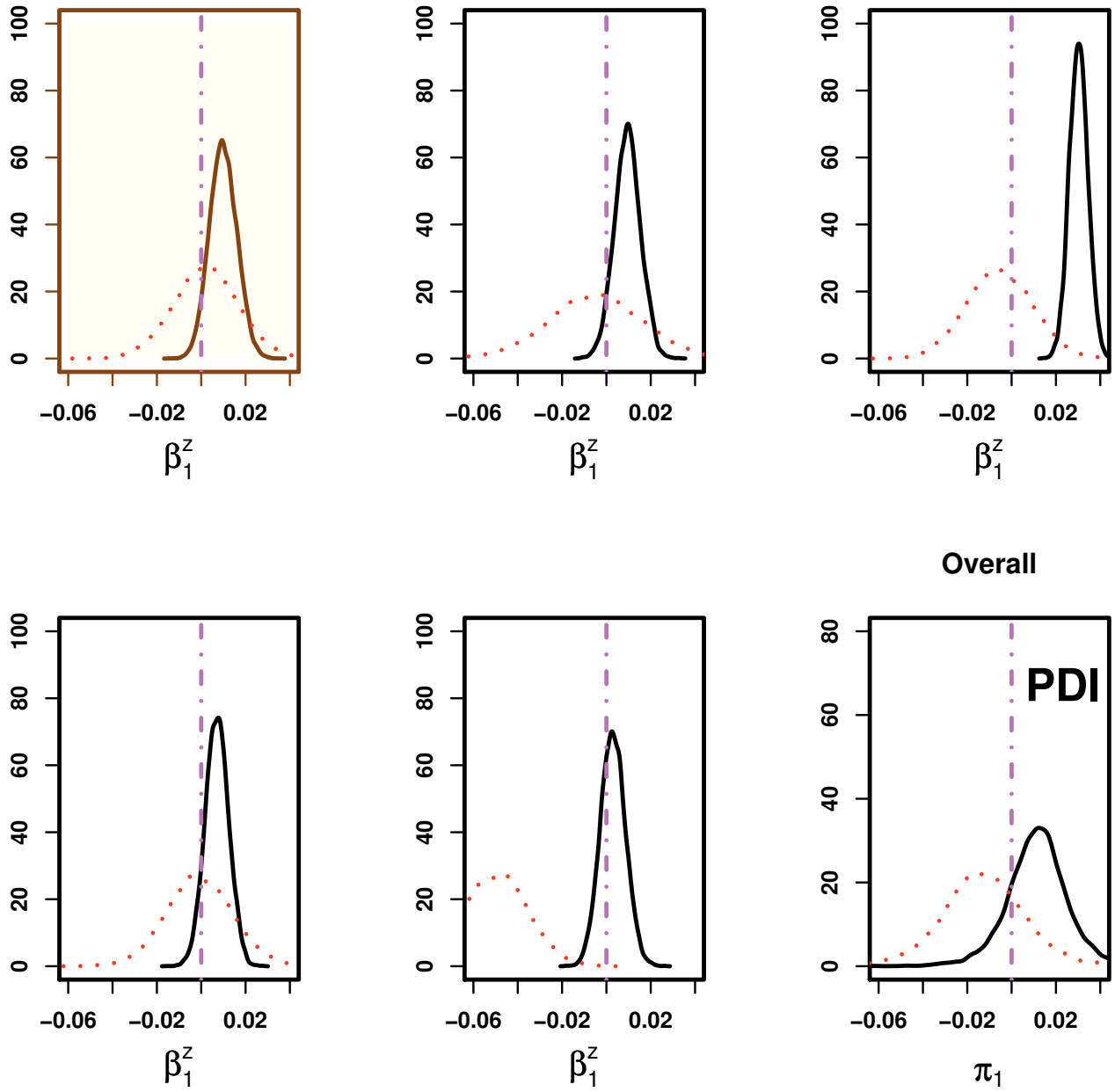
$$
\begin{aligned}
d_m &= \sigma_m^2/\sigma_1^2, \qquad (l, m = 1, 2, 3) \\
\rho_{lm} &= \rho \\
\sigma_{ij1}^2 &= c_0 + c_1(t_j - 1990)
\end{aligned}
$$

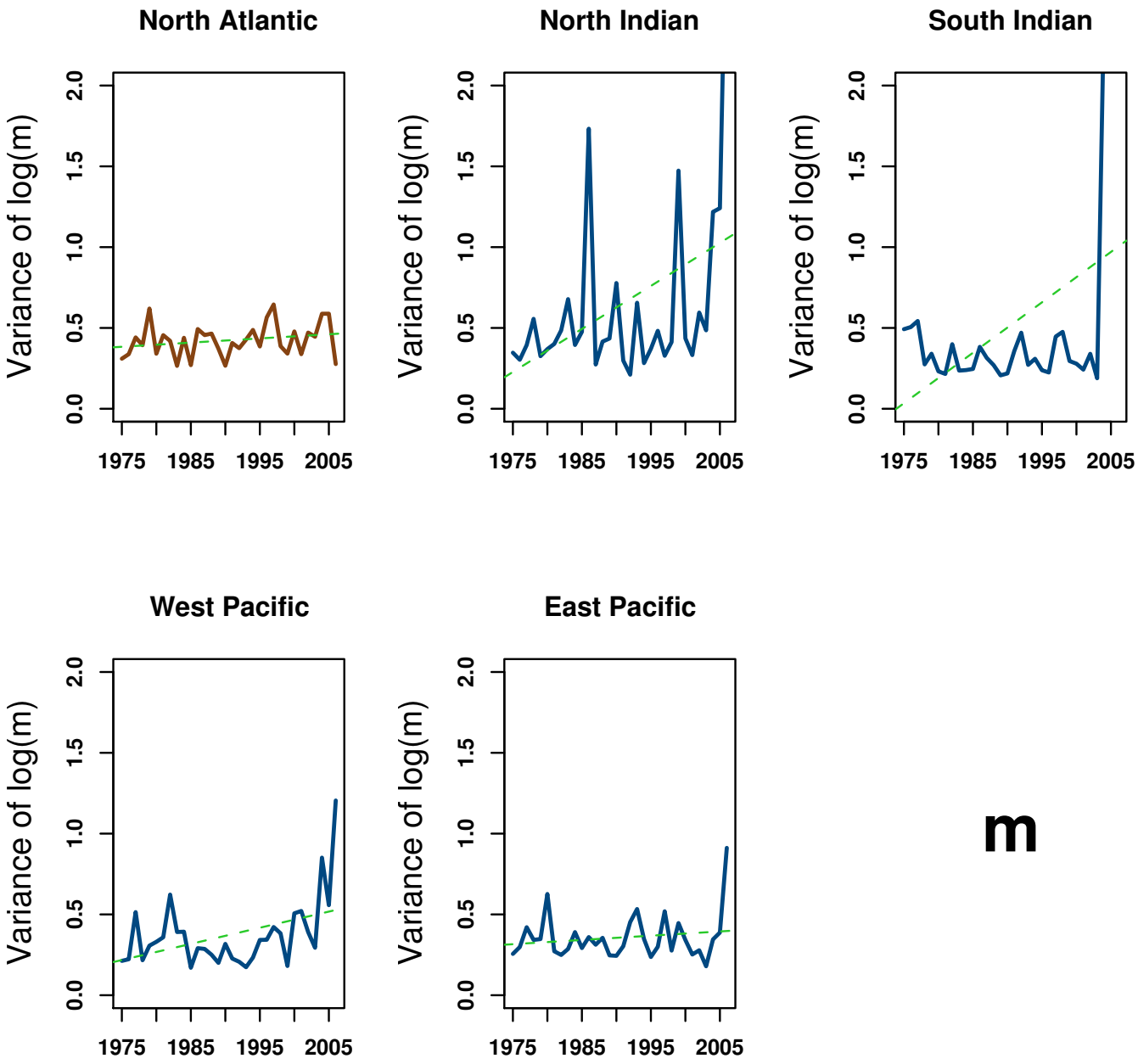
$$
\begin{aligned}
(V_{ij})_{ll} &= d_l \sigma_{ij1}^2 \\
(V_{ij})_{lm} &= \rho\sqrt{d_l d_m}\,\sigma_{ij1}^2
\end{aligned}
$$

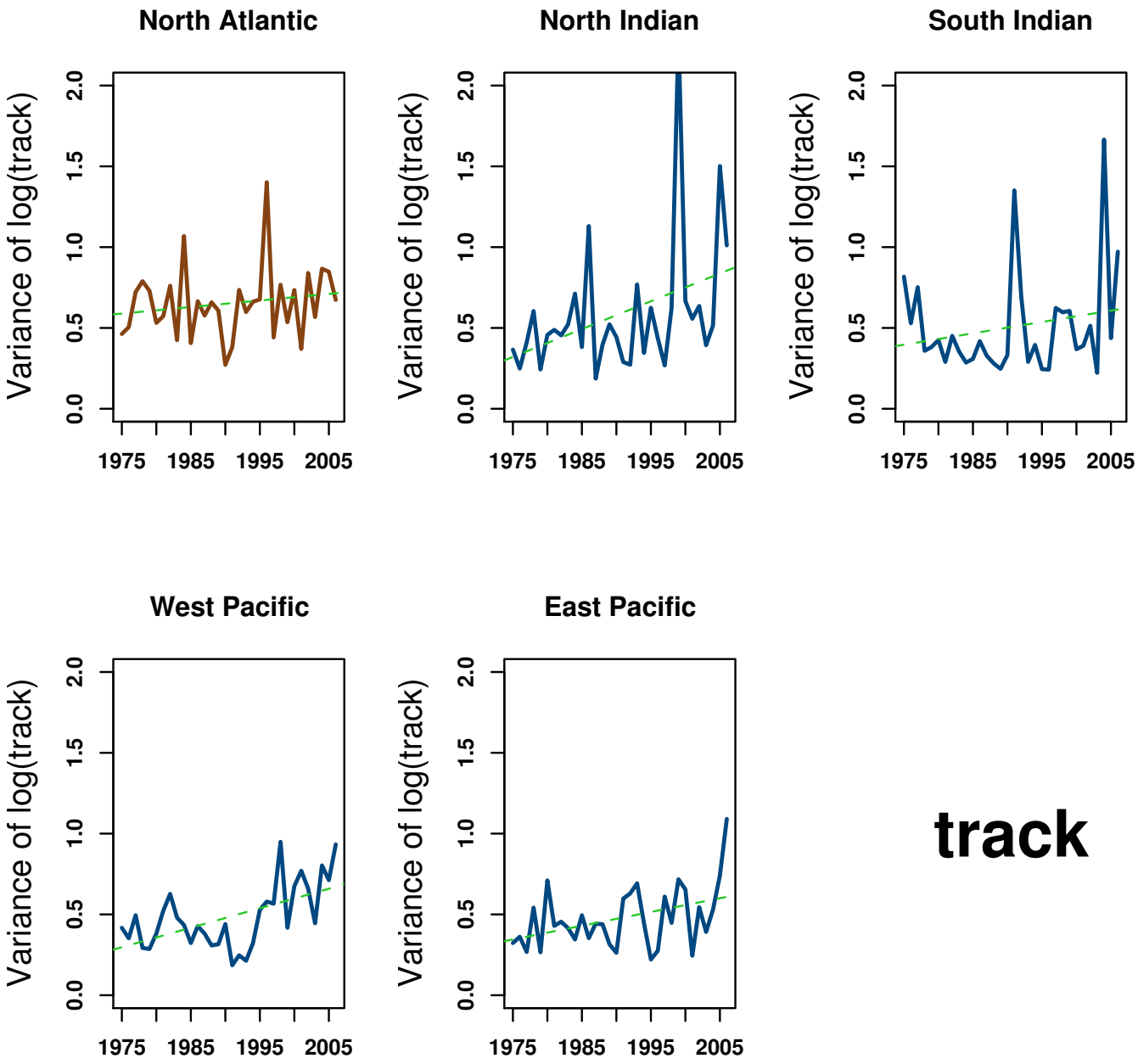
$$
\Lambda_{ij} \sim \text{Wishart}(\mathbf{v}_{ij}, 3)
$$

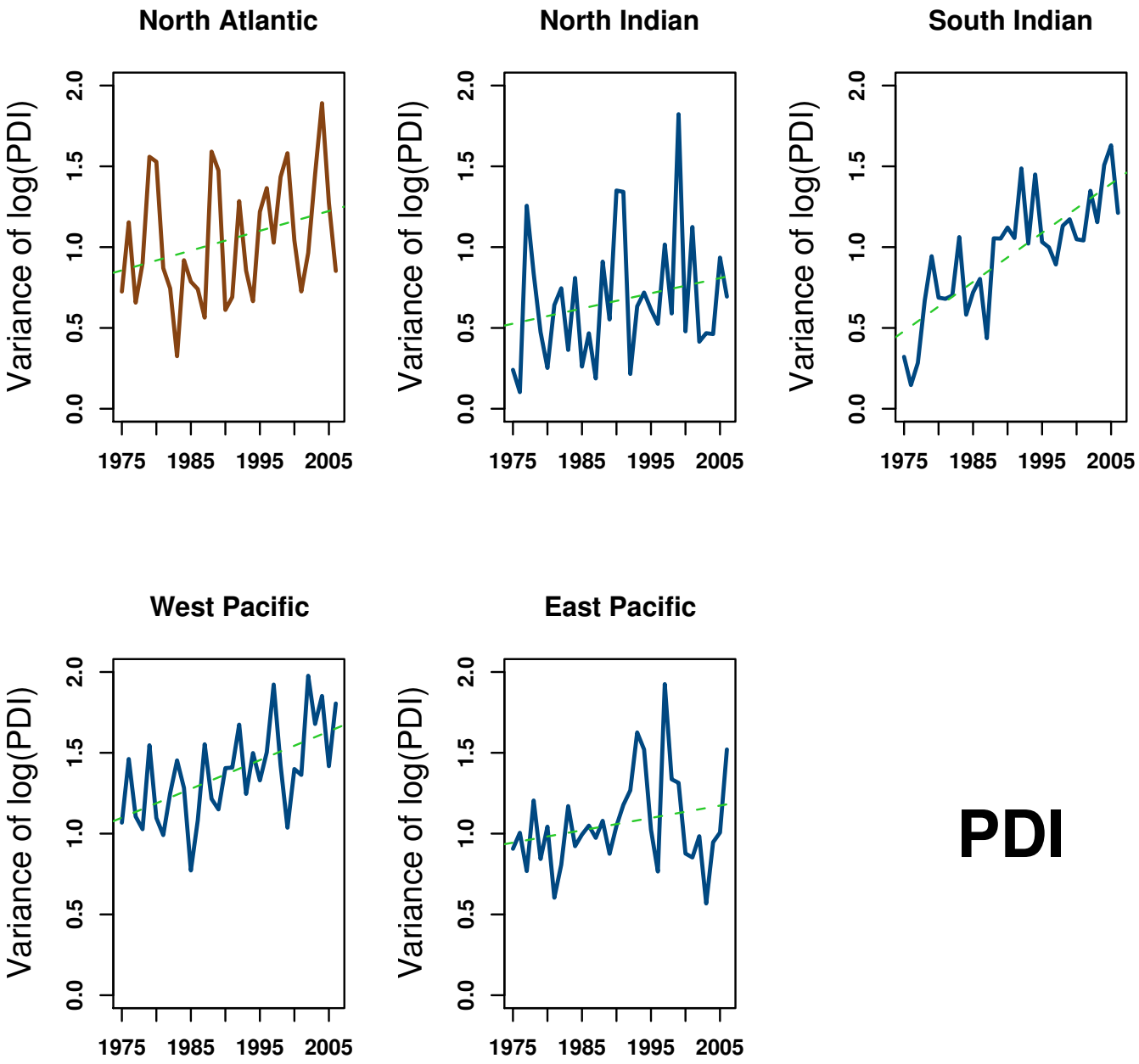

North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Overall
0
20
40
60
80
100
−0.06
−0.02
0.02
β_1^z
π_1
m


0
20
40
60
80
100
−0.06
−0.02
0.02
β_1^z
Overall
track
π_1


0
20
40
60
80
100
−0.06
−0.02
0.02
β_1^z
Overall
PDI
π_1


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Variance of log(m)
0.0
0.5
1.0
1.5
2.0
1975
1985
1995
2005
m


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Variance of log(track)
0.0
0.5
1.0
1.5
2.0
1975
1985
1995
2005
track


North Atlantic
North Indian
South Indian
West Pacific
East Pacific
Variance of log(PDI)
0.0
0.5
1.0
1.5
2.0
1975
1985
1995
2005
PDI

Effect of CTI/NAOI/AMO on log(m)

Ocean	2.5%	50%	97.5%
	β_2^z: CTI		
WP	**0.10**	**0.16**	**0.22**
	β_3^z: NAOI		
	none		
	β_4^z: AMO		
	none		

Effect of CTI/NAOI/AMO on log(track)

Ocean	2.5%	50%	97.5%
	β_2^z: CTI		
NI	**0.05**	**0.15**	**0.26**
WP	**0.13**	**0.21**	**0.28**
	β_3^z: NAOI		
	none		
	β_4^z: AMO		
	none		

Effect of CTI/NAOI/AMO on log(PDI)

Ocean	2.5%	50%	97.5%
	β_2^z: CTI		
WP	**0.13**	**0.25**	**0.37**
	β_3^z: NAOI		
	none		
	β_4^z: AMO		
	none		

Conclusions

1. Globally, the number of storms has *not* increased.

2. Globally, the rate at which storms became hurricanes has *not* increased.

3. Globally, the rate at which hurricanes became category 4+ storms *may* have increased.

Conclusions (cont.)

1. Intensity has increased from 1975, but *not* from 1990.

2. Data quality is always suspect.

3. So it all depends on where you start looking.

Future work

1. Apply analysis to Kossin, Knapp et al. satellite-statistical-*derived* database.

2. Investigate more sophisticated models for satellite-statistical-*derived* databases.