Record-Breaking Increase in Taiwan Typhoon Rainfall in the 21st Century: Is It Related to Global Warming?

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Outline

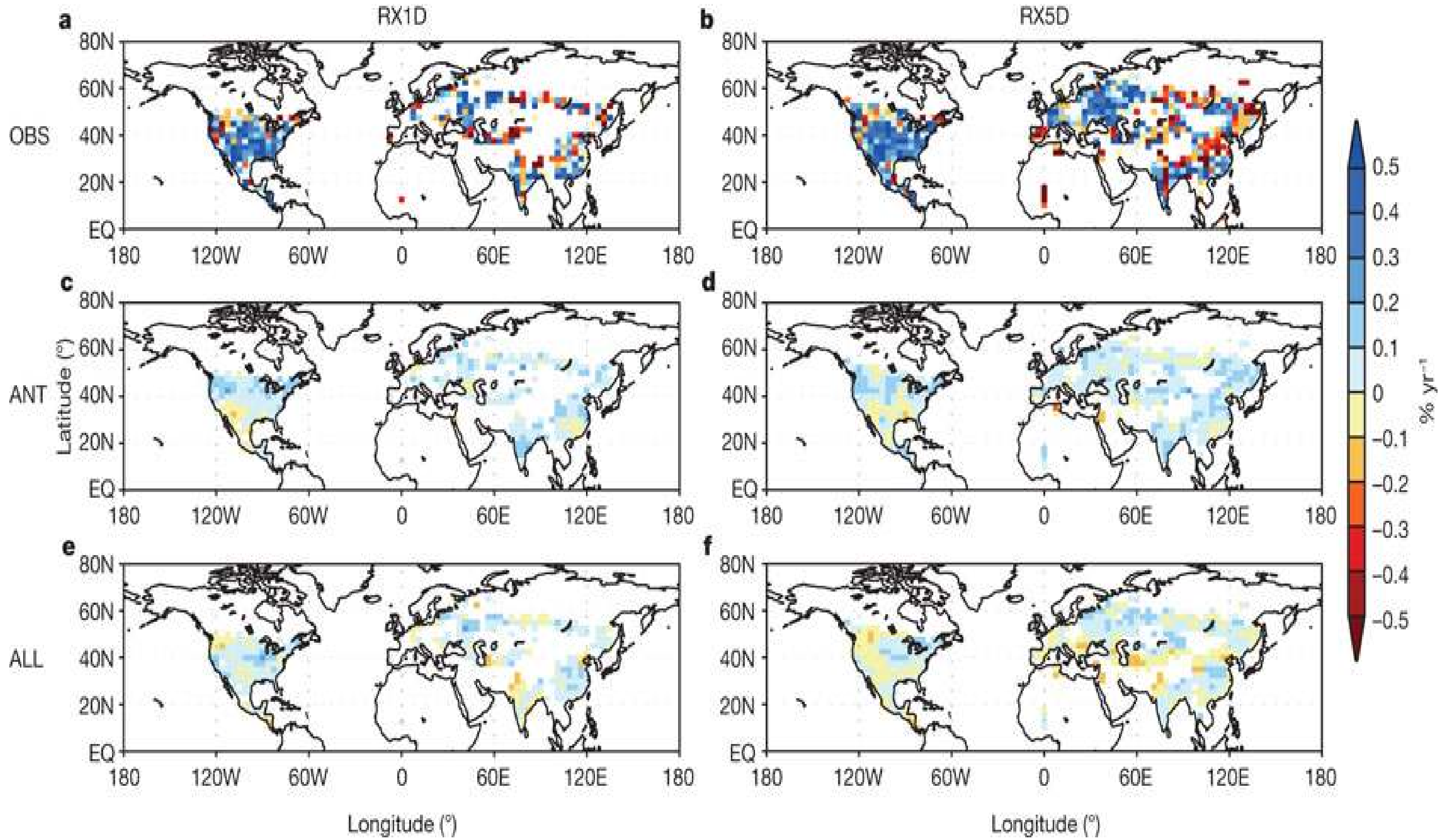
1. TC and China Summer Monsoon Extreme Rainfall (90th percentile) 1958-2010

2. TC Rain Intensity in Taiwan 1961-2011(2013)

Introduction

- Global Warming → Increasing vapor capacity → increasing rain intensity and extreme rainfall.
- Increasing trend of extreme rainfall simulated over NH land area; correspondence good over Europe & N. America, but mixed over Asian monsoon region.
- Very large increasing trend of extreme rainfall reported in Taiwan since 1998, attribution to global warming is the subject of ongoing debate.
  (2008 Typhoon Morakat →, Change of government)

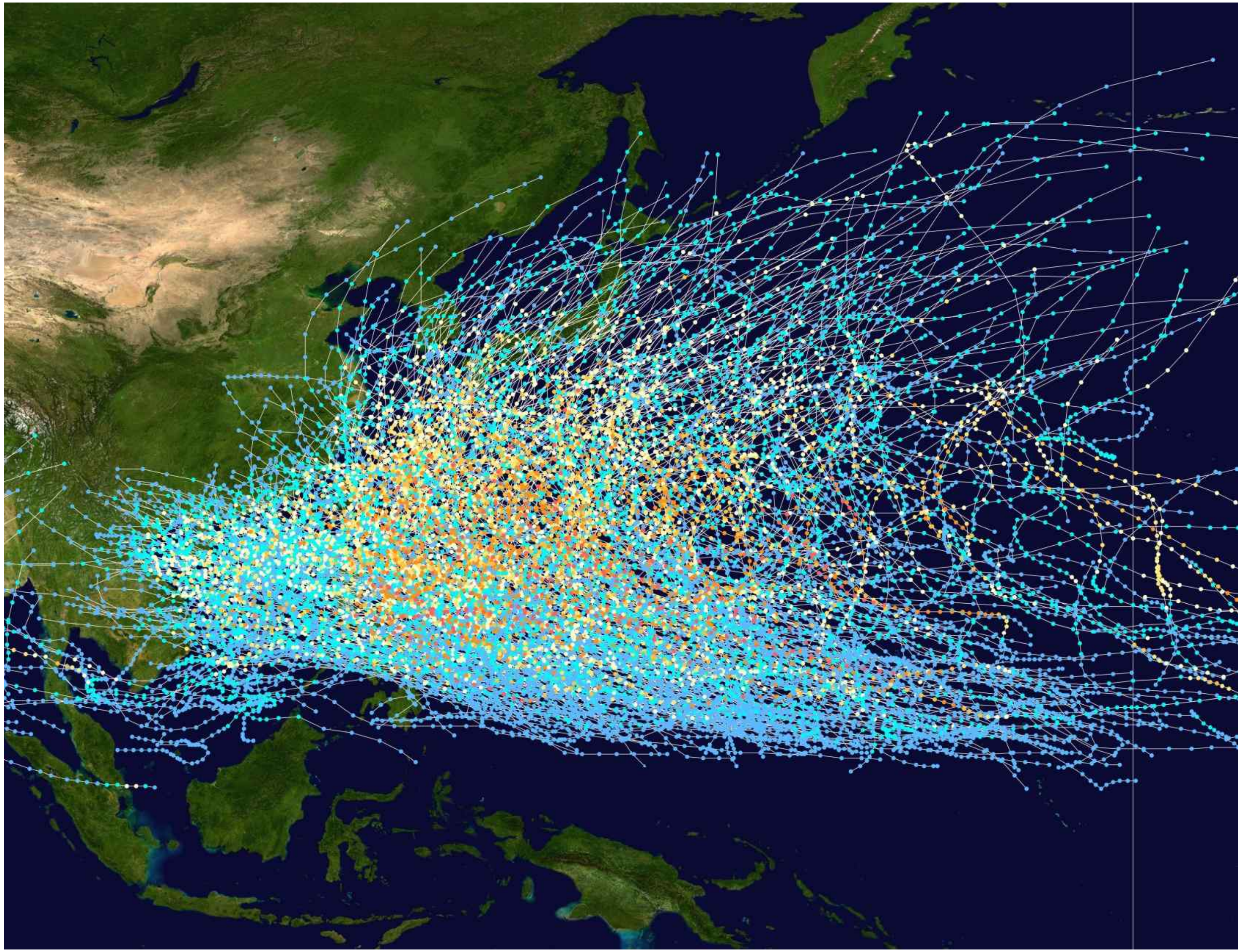
Global distribution of trends of extreme precipitation indices (PI) during 1951–99.



S-K Min *et al. Nature* **470**, 378-381 (2011) doi:10.1038/nature09763

nature

Taiwan is situated in one of the main paths of western North Pacific tropical cyclones (TCs)



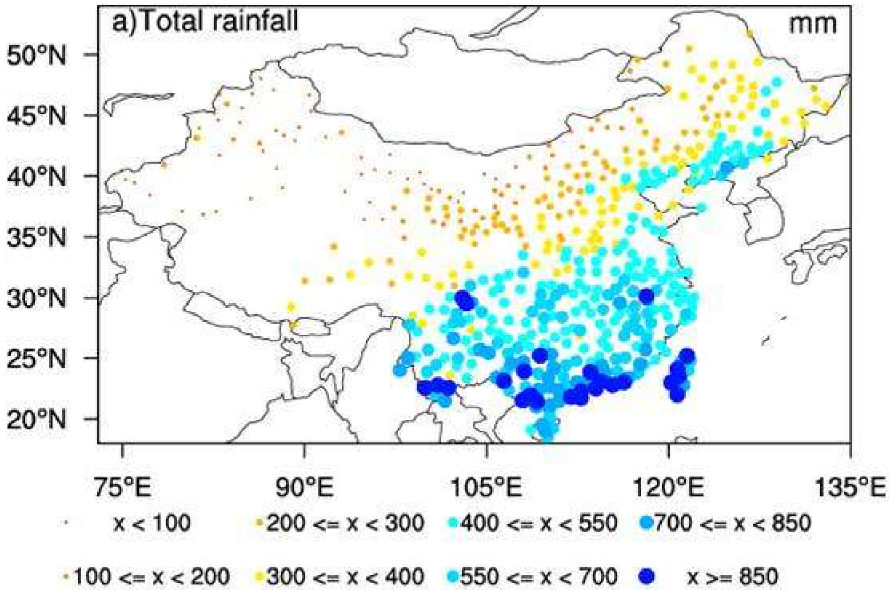
Rainfall in East Asia Summer Monsoon

- Extreme rainfall contributed by both monsoon and Tropical Cyclones (TCs)
- TCs influenced by tropical western North Pacific conditions (upstream of East Asian landmass)
- Extreme rainfall influenced by external factors not part of local thermodynamic conditions

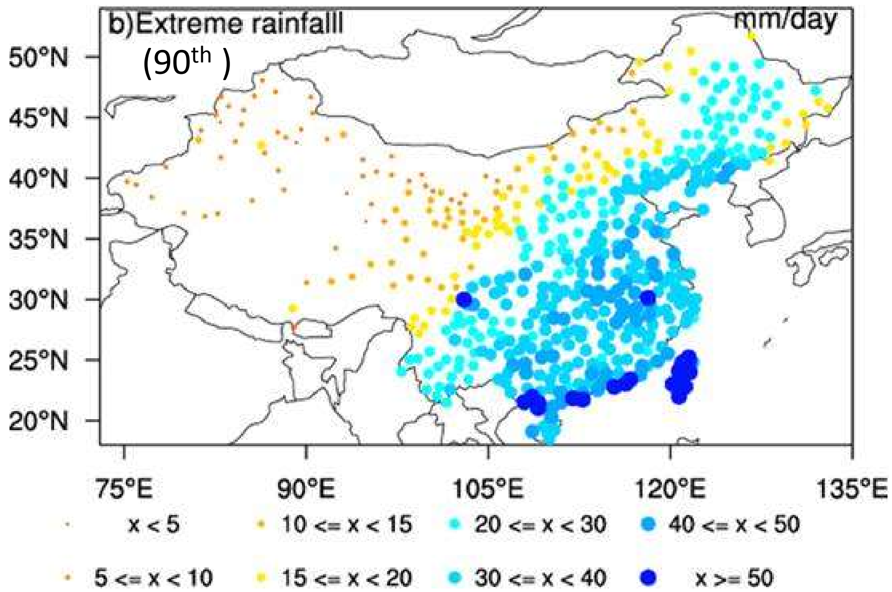
TC and China Summer Monsoon Extreme Rainfall Data

- JJA 1958-2010, 53 years;
- Daily rain stations: 479 (of 776) from China mainland, 20 from Taiwan;
- Extreme rainfall defined locally at 90^{th} percentile;
- Each rain day is either TC or Monsoon (non-TC);
- TC events identified with Objective Synoptic Analysis Technique (OSAT, Ren *et al.,* 2006), Influence range 500-1100 km.

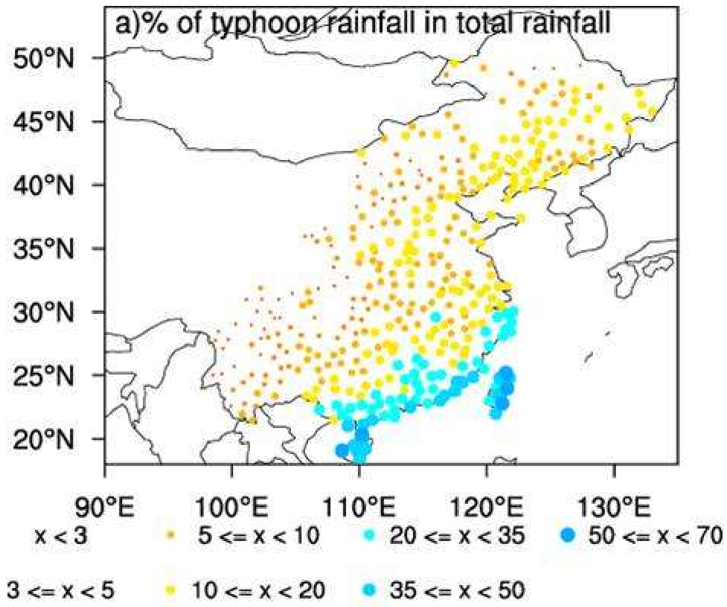
Total Rainfall



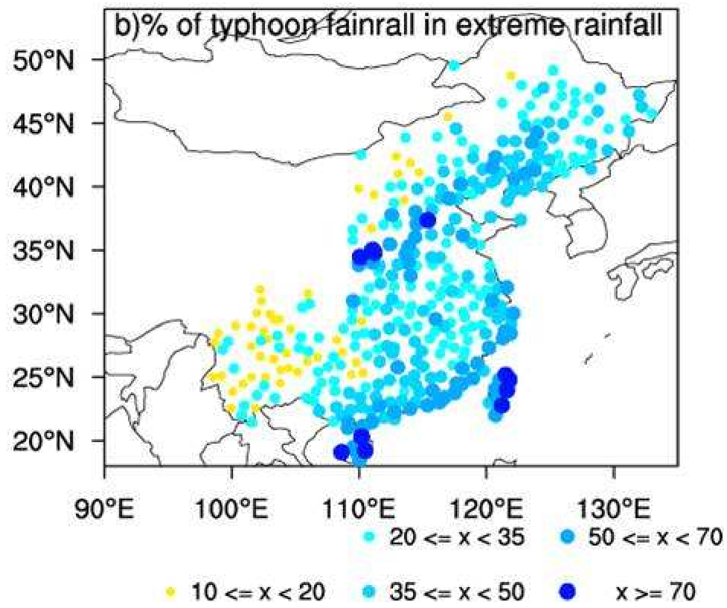
Extreme Rainfall



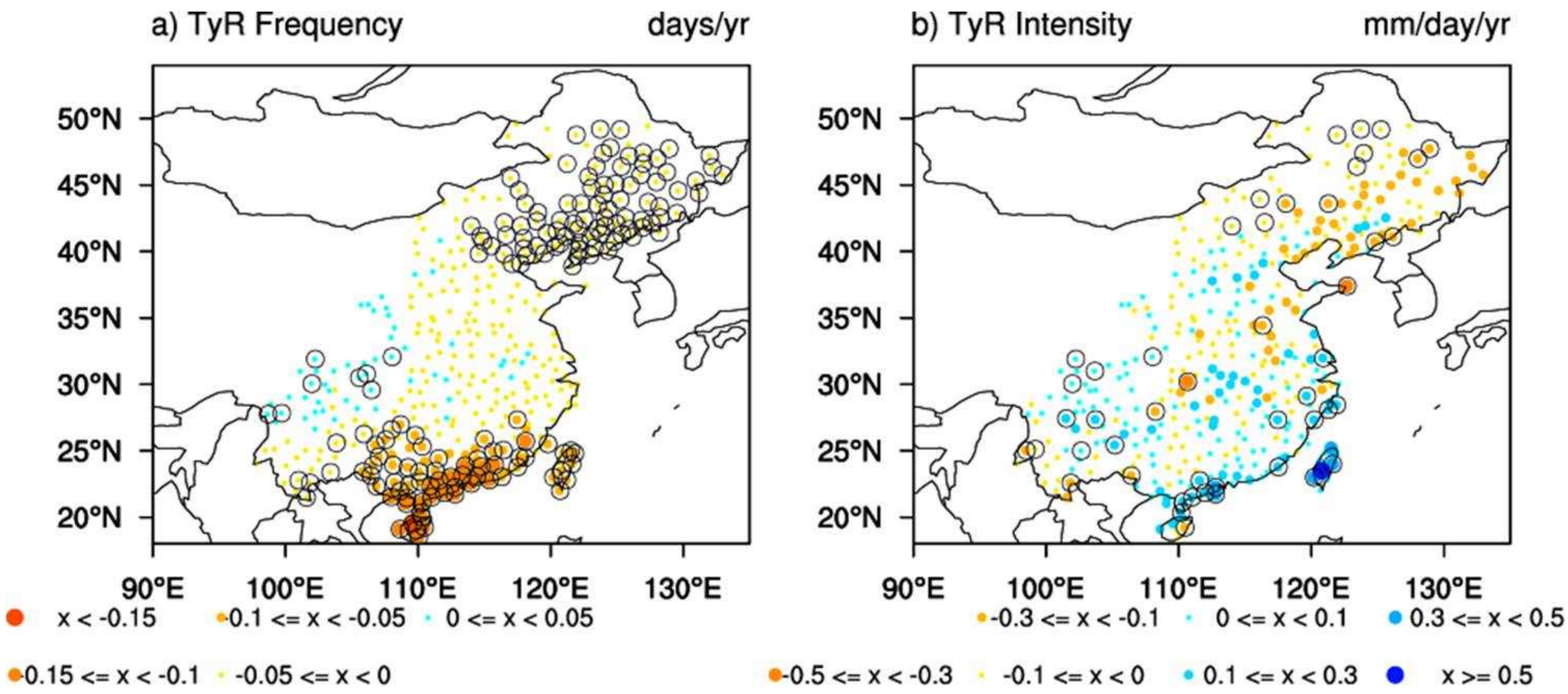
Percentage of TC rainfall in Total Rainfall



Percentage of TC rainfall in Extreme Rainfall

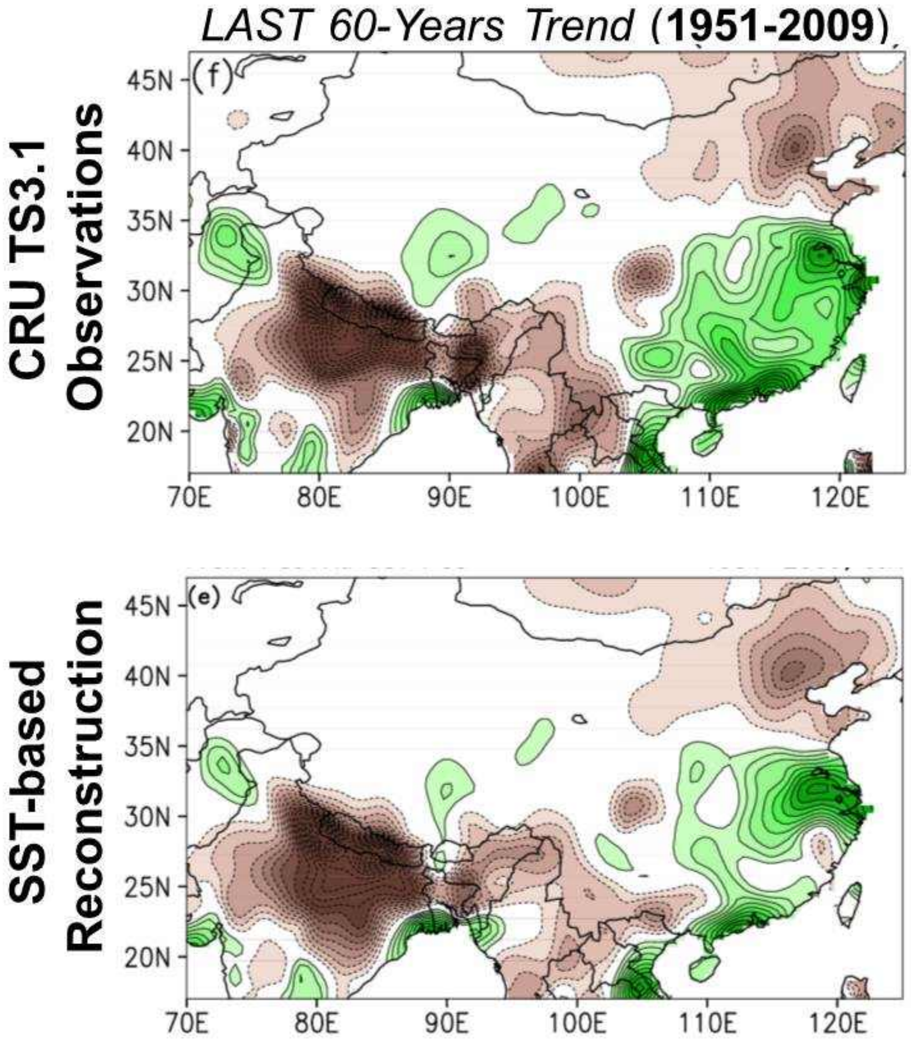


Typhoon rainfall linear trends



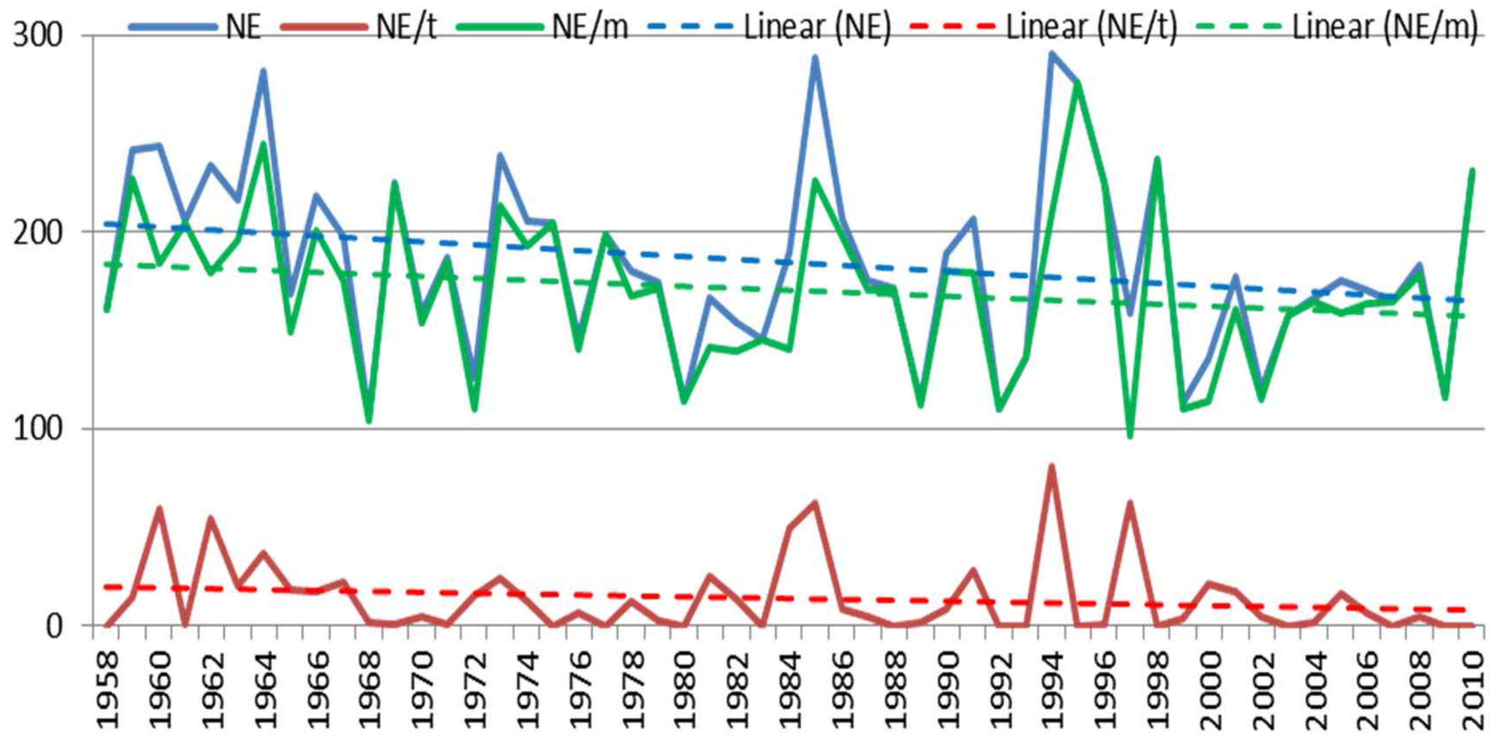
Frequency ↓ Intensity ↑

South-Flood North-Drought (SFND)



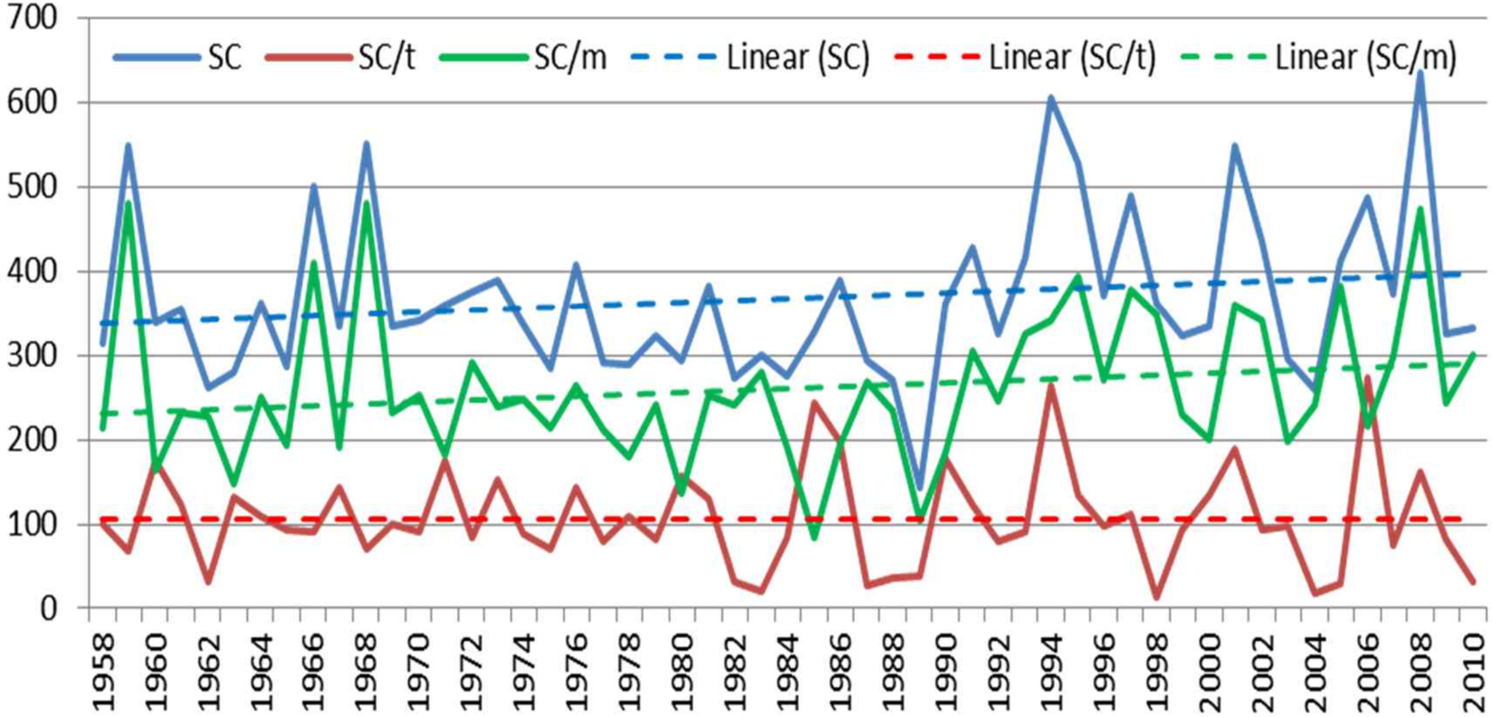
Nigam and Zhou (2012)
NTU International Science Conference on Climate Change

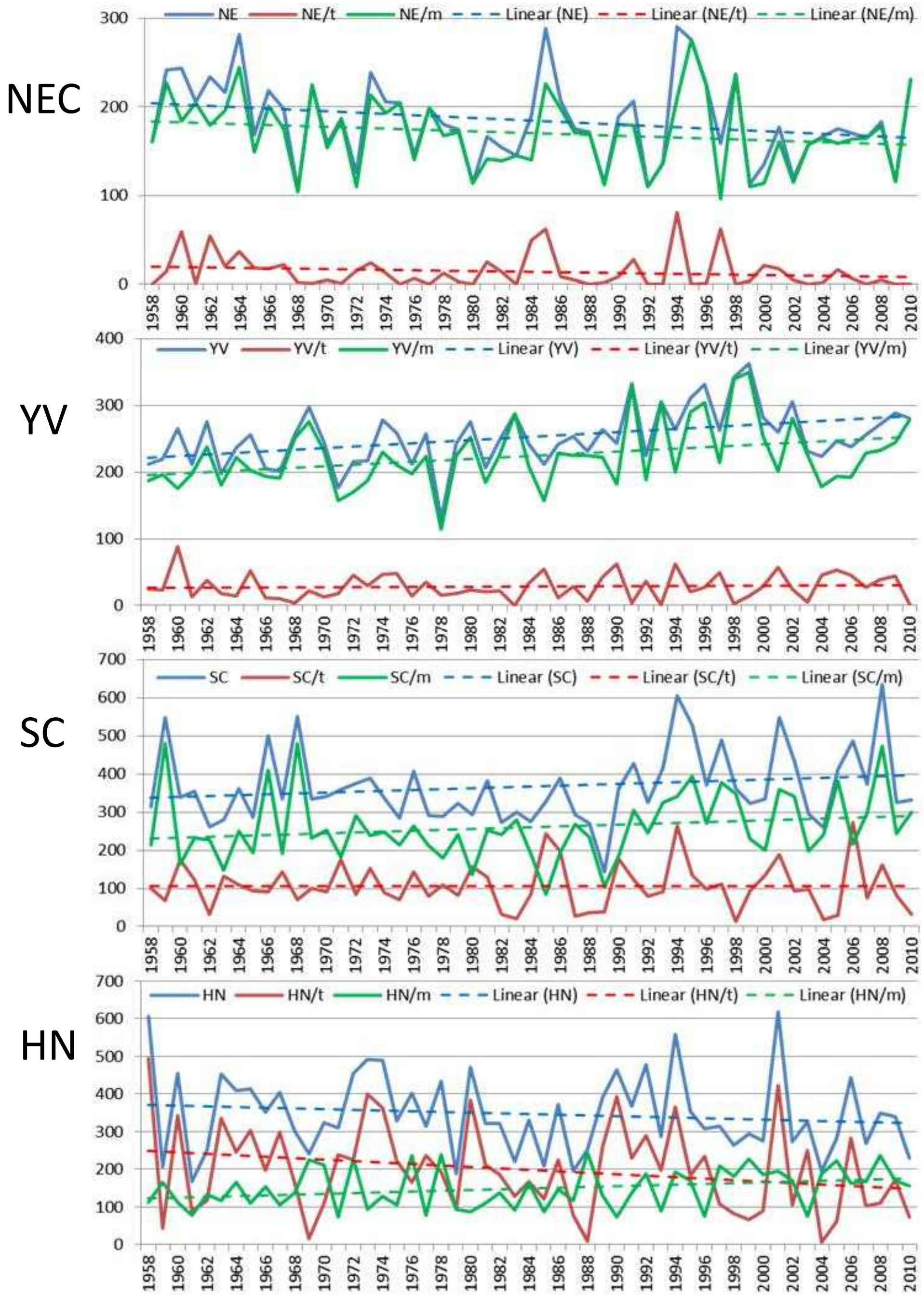
NE China

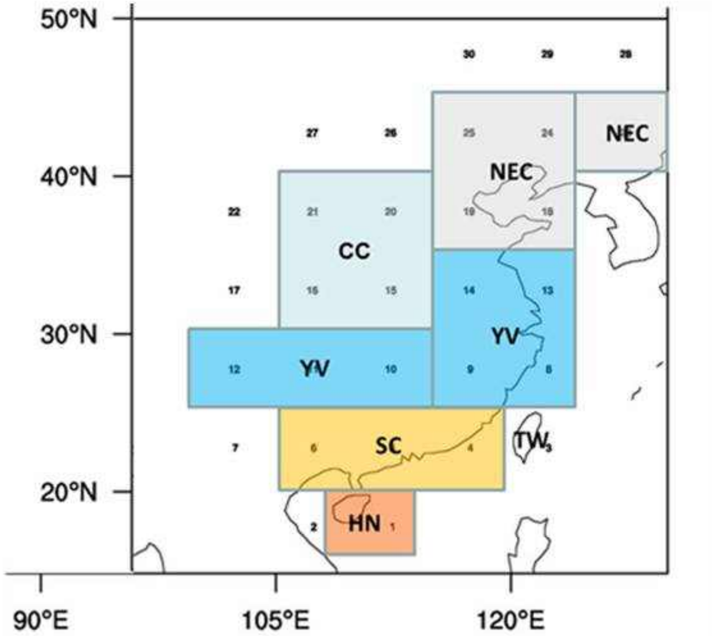


NE
NE/t
NE/m
Linear (NE)
Linear (NE/t)
Linear (NE/m)
300
200
100
0
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

Southern China

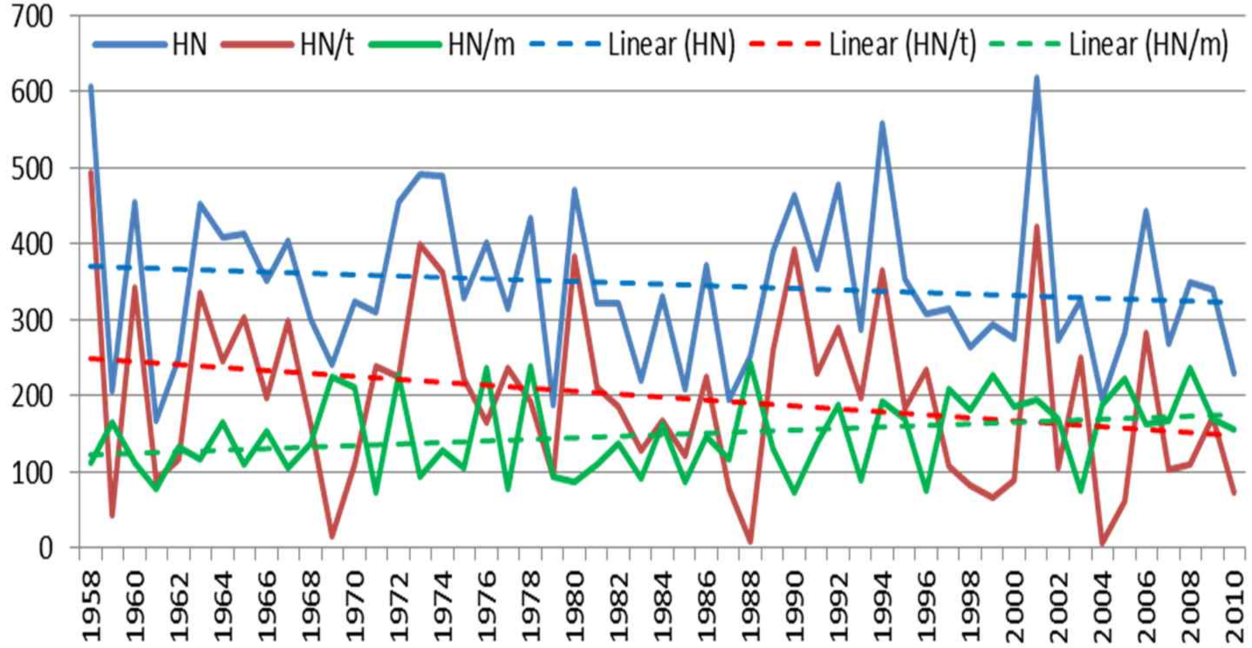






	Total	Monsoon	underestimate
NE China	**-21.4%**	-16.3%	32%
Central China	6.5%	7.3%	11%
Yangzi Valley	***25.1%***	***26.1%***	4%
Southern China	16.5%	**23.3%**	29%
Hainan Island	-14.8%	**35.1%**	∞

Hainan



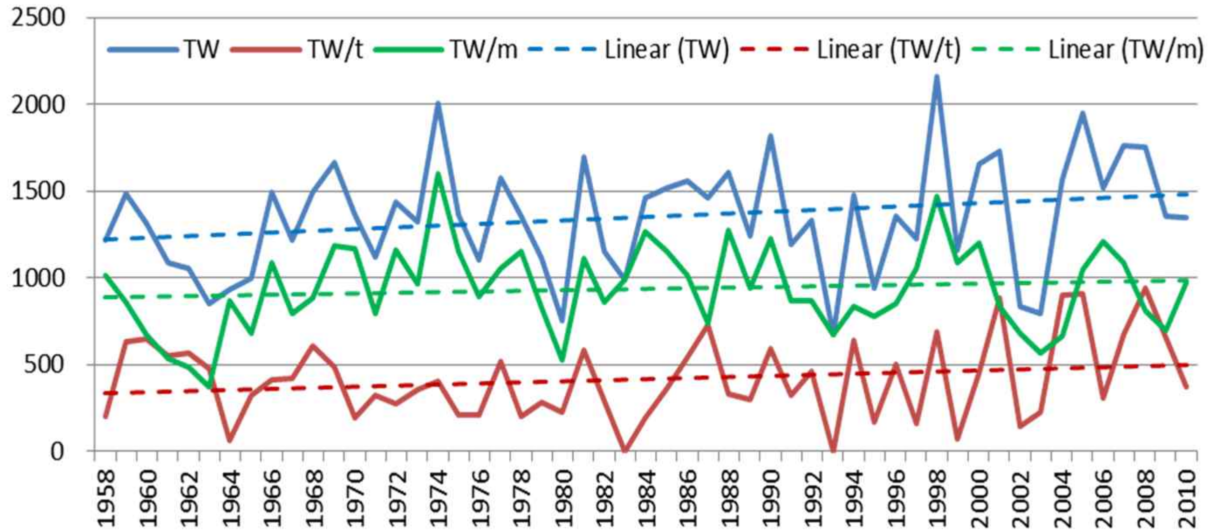
Total -14.8%

Monsoon 35.1%

Underestimate

$\propto$

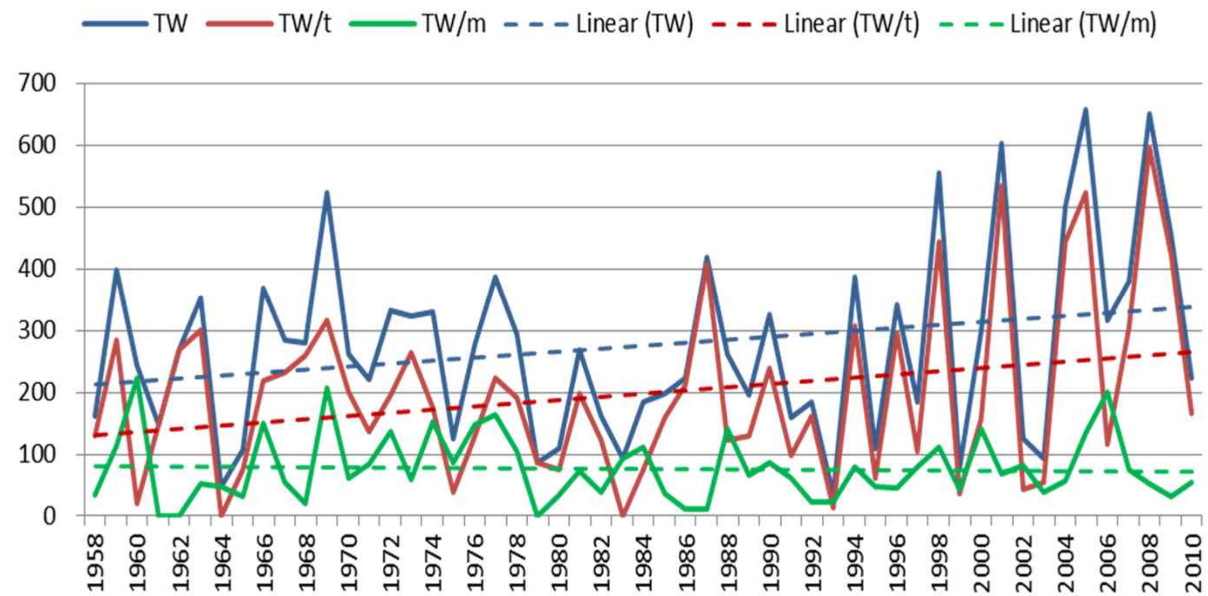
Taiwan



Total 19.5%

Monsoon 10.9%

Overestimate
~ 79%



Total 46.2%

Monsoon -12.2%

Overestimate ∞

Monsoon extreme rainfall trend (XRT)

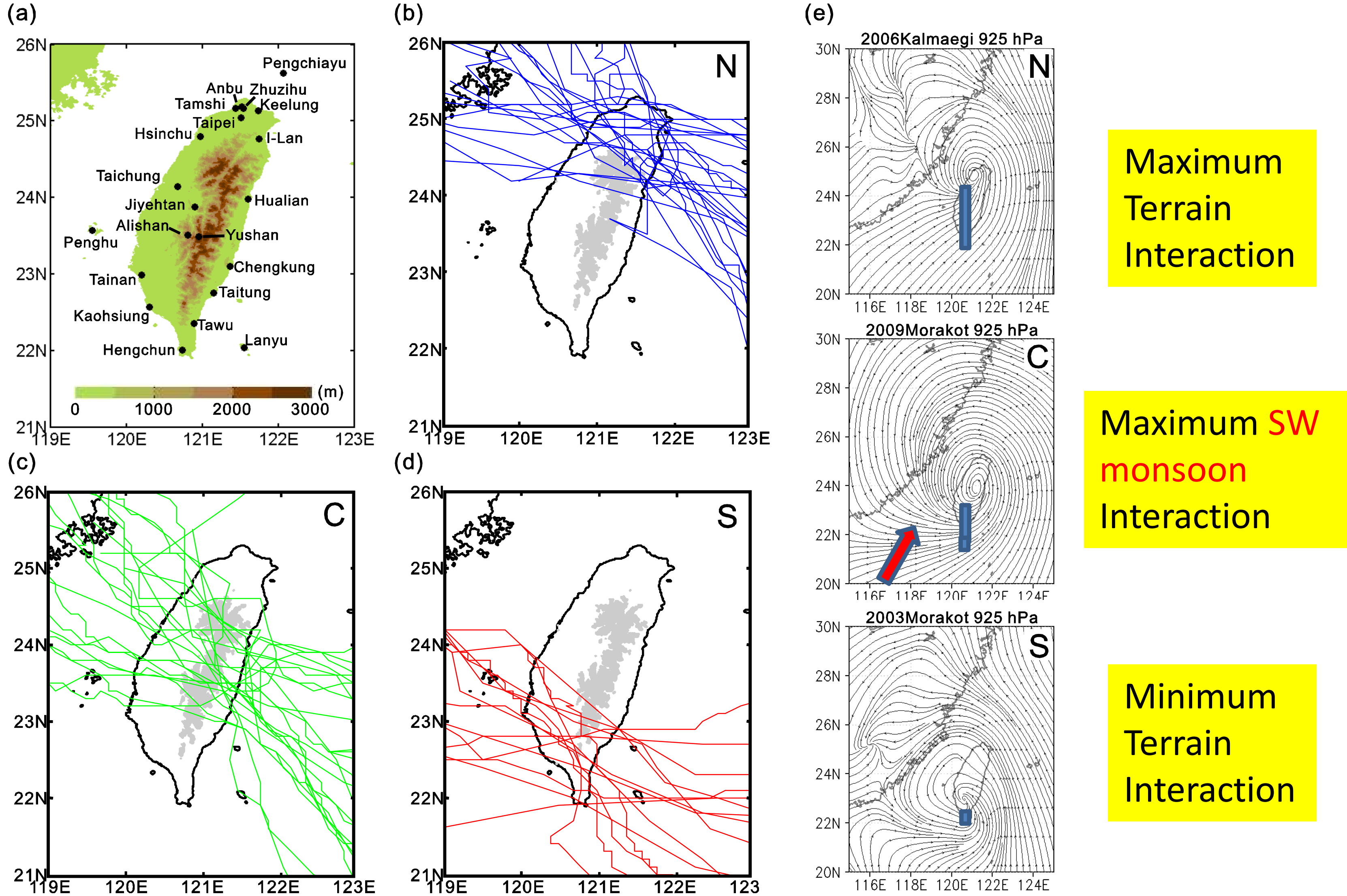
- Since mid-20C, Decreasing TC rainfall frequency dominate increasing TC rainfall intensity. In most region TC XRT < monsoon XRT.
  - Intrinsic monsoon XRT is underestimated.
- Sign remains mostly negative in NE China.
  - A broader scale positive trend may emerge if SFND variation can also be isolated?
- Drastically opposite effects on Hainan and Taiwan.
  - Large Taiwan XRT cannot be attributed to thermodynamic effect of global warming.

Taiwan Typhoon Rain Intensity

- 21 hourly stations 1960-2011(2014)
- 84 landfalling typhoons (all seasons)
- Re-analyzed TC tracks by CWB & NTU, focusing on the three leading Types: **N**, **C**, **S**
- 3 Track Phases: **PR**e-landfall, **O**ver**L**and, **EX**it
- Rainfall affected by
    - Interaction with Terrain
    - Interaction with Monsoon

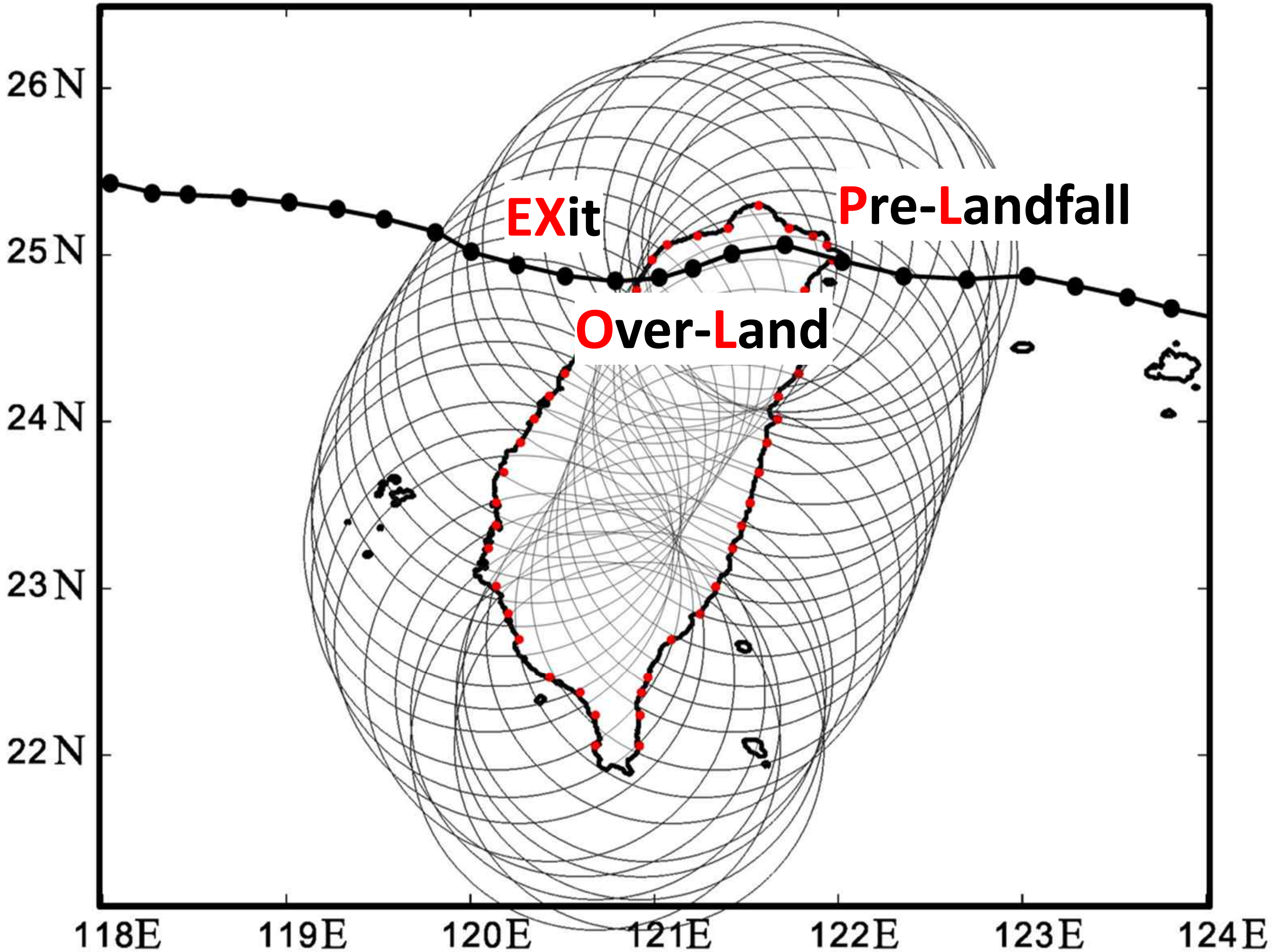
Table 1: The twelve typhoons in 1960-2011 with total rainfall over Taiwan exceeding 3500 mm during the three phases. The eight since 2004 are highlighted.

Rank	Year	Typhoon Name	Total (h)	Rainfall (mm)
1	**2009**	**Morakot**	**45**	**8996**
2	**2001**	**Nari**	**75**	**8108**
3	**2008**	**Sinlaku**	**48**	**8105**
4	**2005**	**Haitang**	**32**	**5589**
5	1996	Herb	16	4836
6	1989	Sarah	38	4655
7	1960	Shirley	24	4637
8	**2007**	**Krosa**	**23**	**3936**
9	**2004**	**Mindulle**	**41**	**3856**
10	**2008**	**Jangmi**	**25**	**3800**
11	**2008**	**Kalmaegi**	**23**	**3763**
12	**2005**	**Talim**	**17**	**3526**

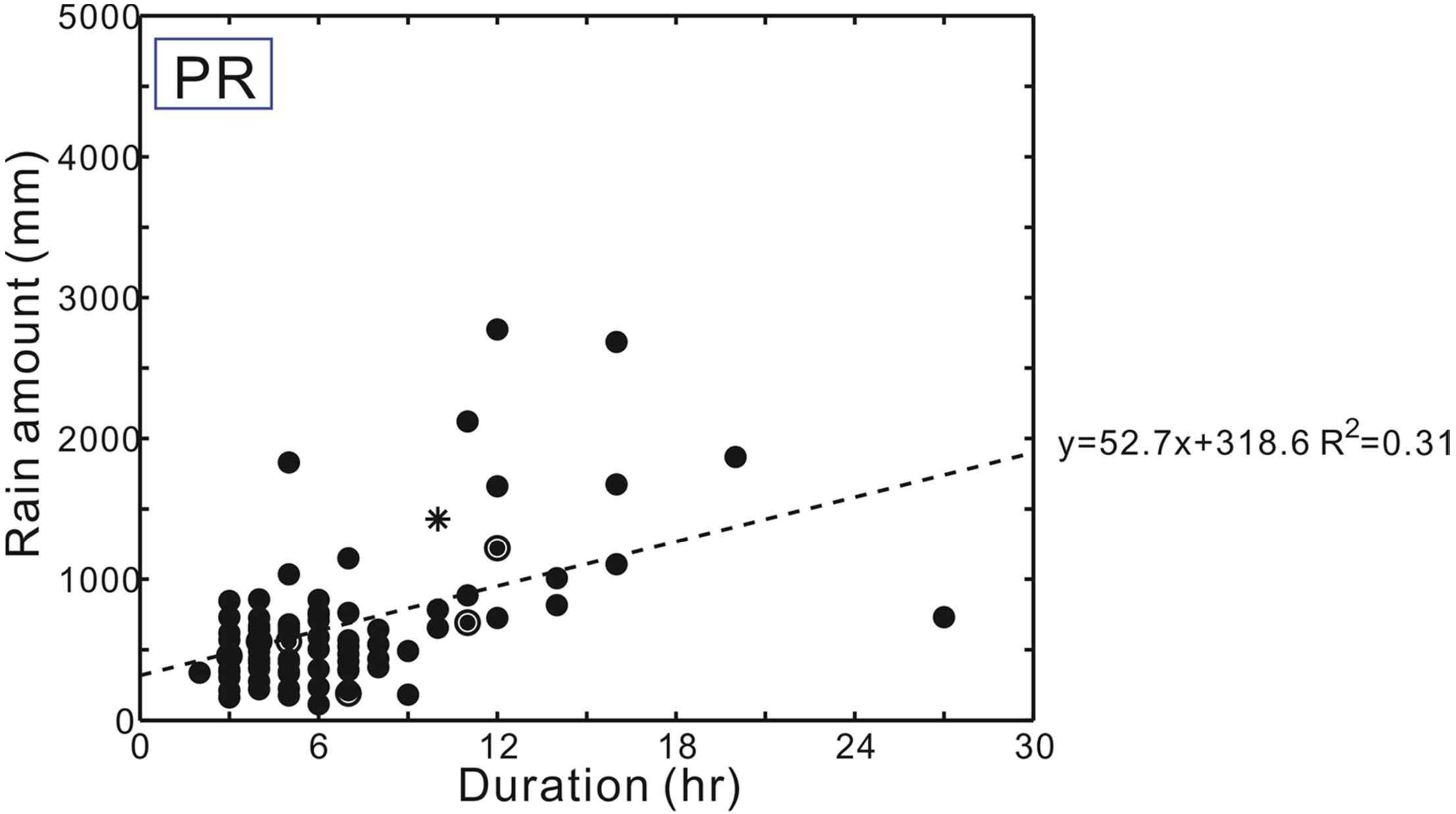


1960-2011: 21 hourly stations , 84 landfalling typhoons

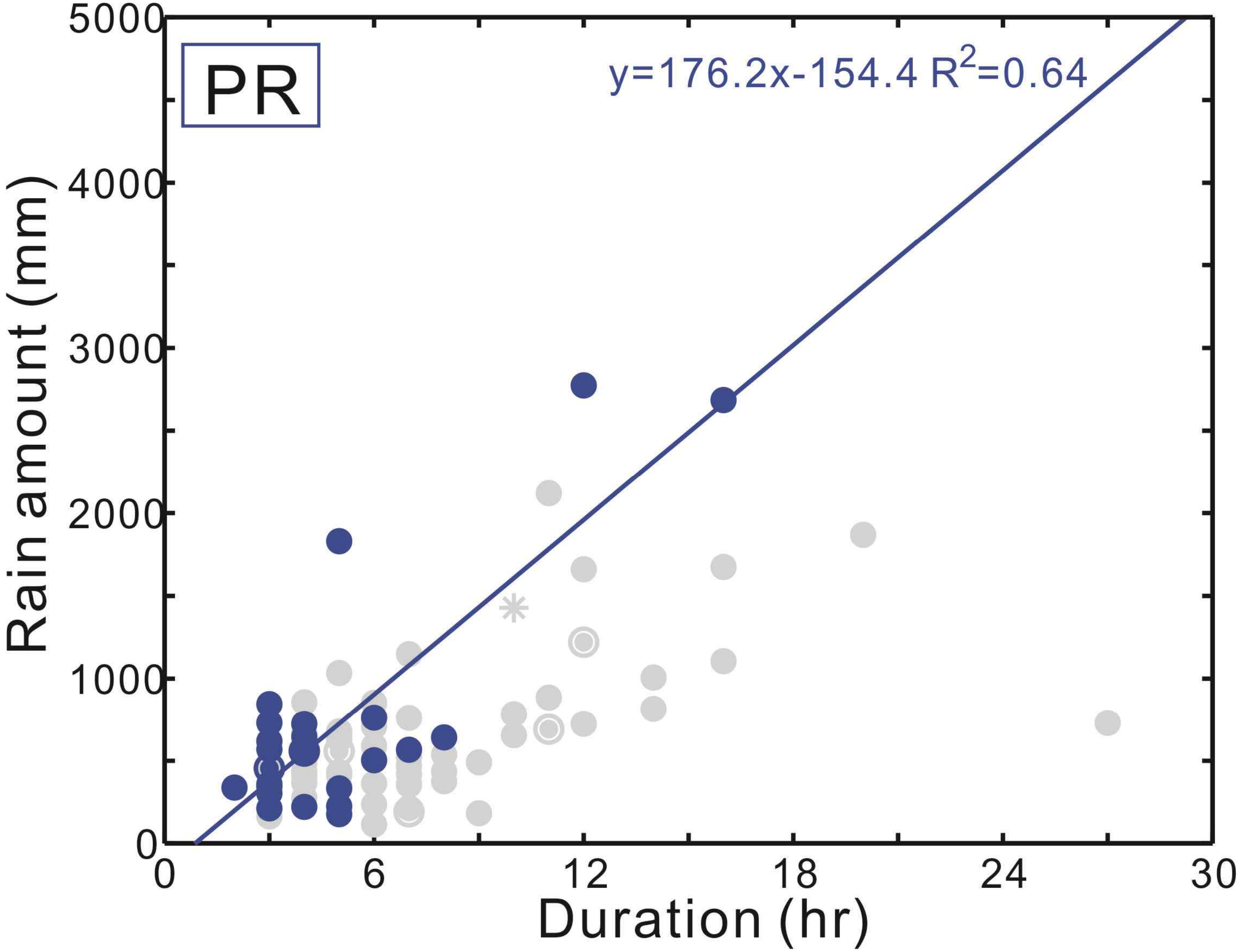
Typhoon Track Phases

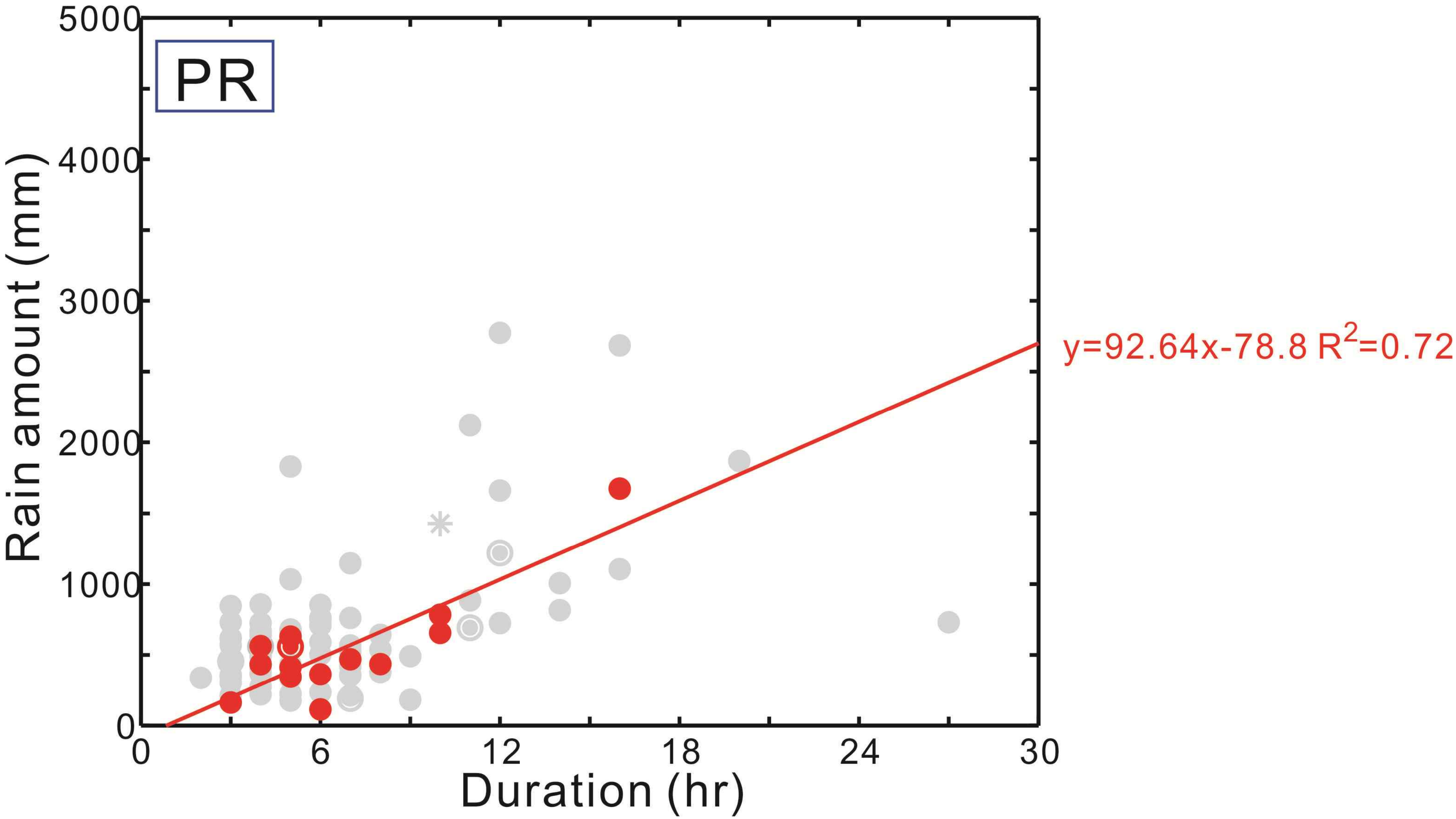


PR

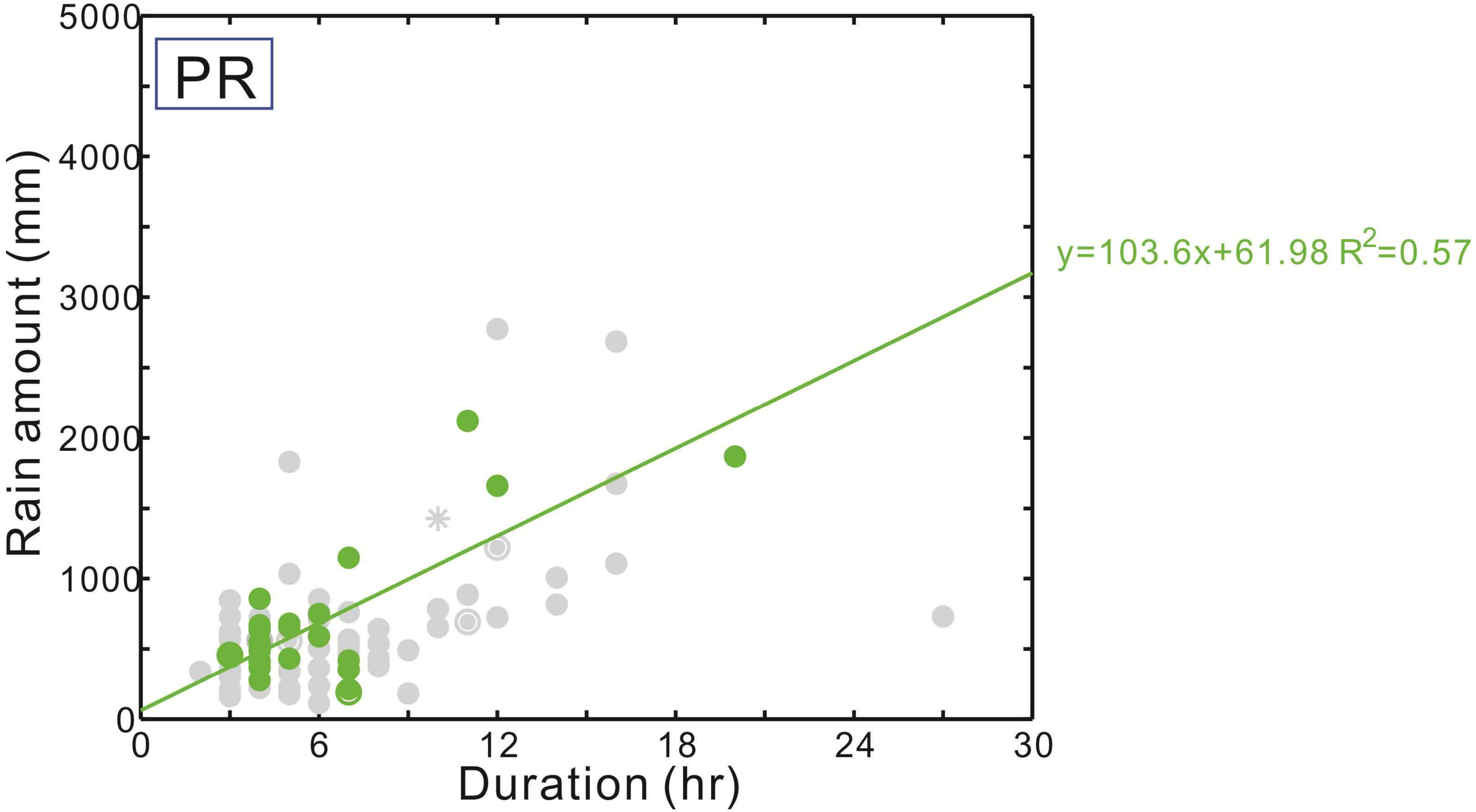


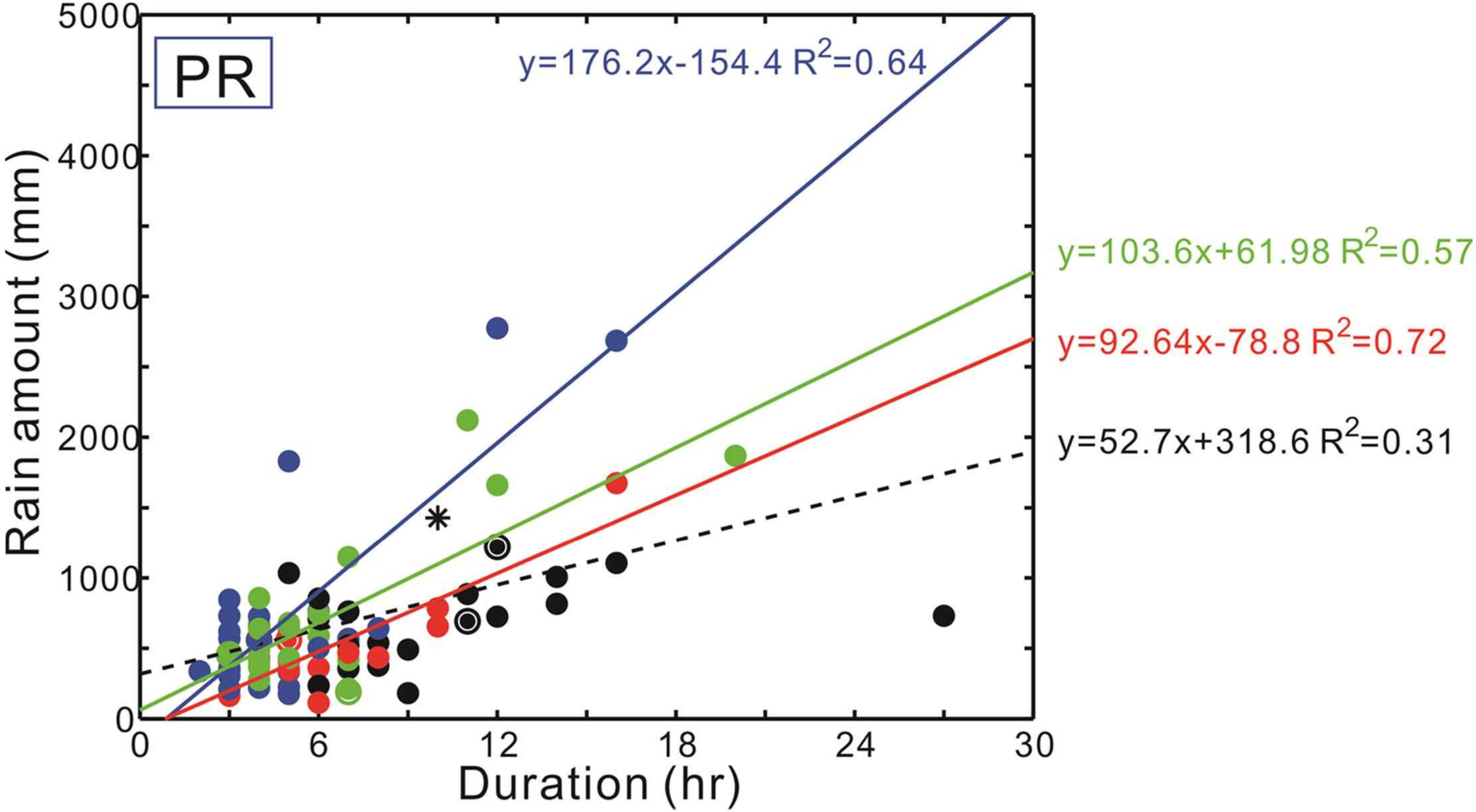
PR
Rain amount (mm)
5000
4000
3000
2000
1000
0
0
6
12
18
24
30
Duration (hr)
y=52.7x+318.6 R2=0.31

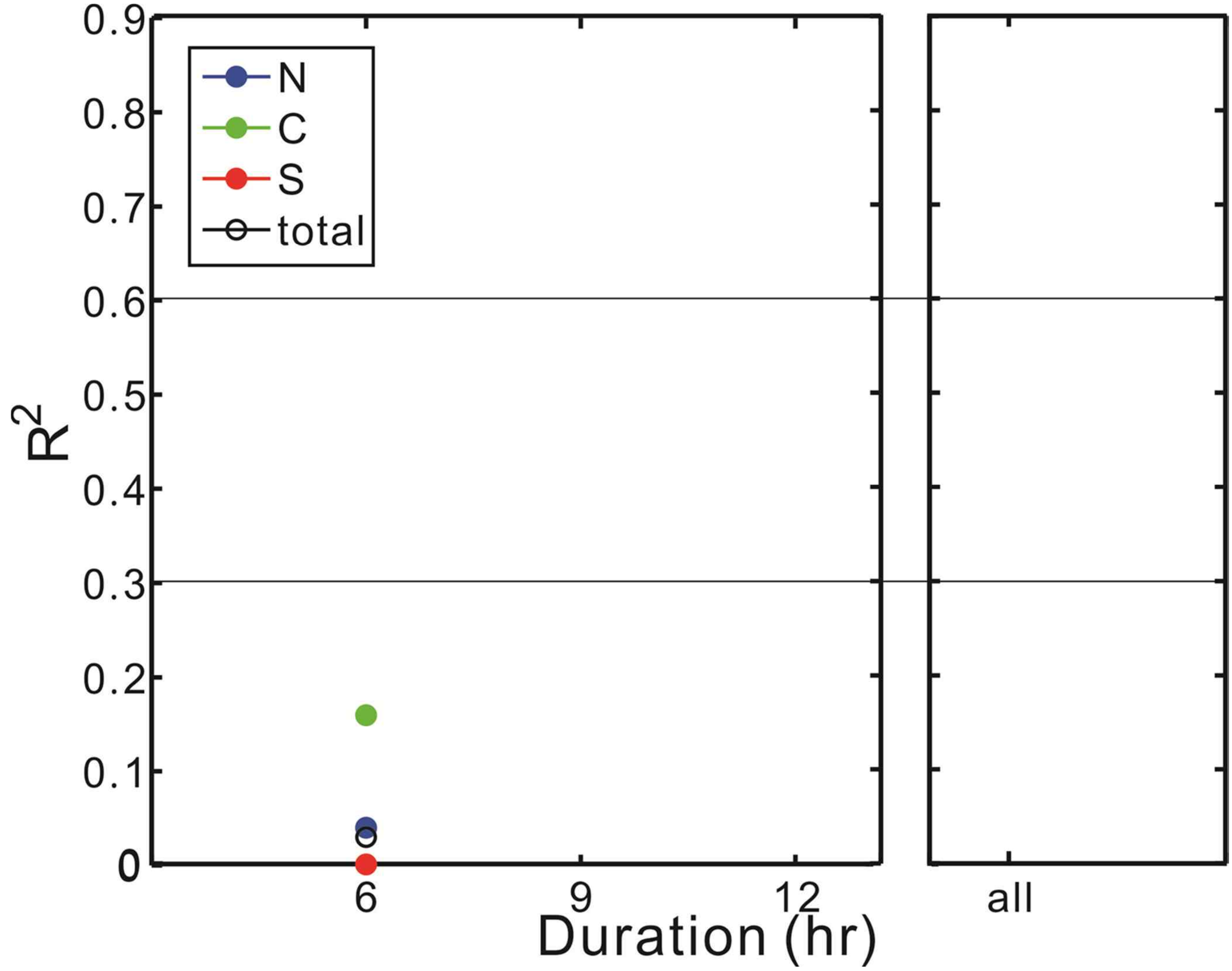

PR
y=176.2x-154.4 R^2=0.64
Rain amount (mm)
Duration (hr)
0
1000
2000
3000
4000
5000
0
6
12
18
24
30



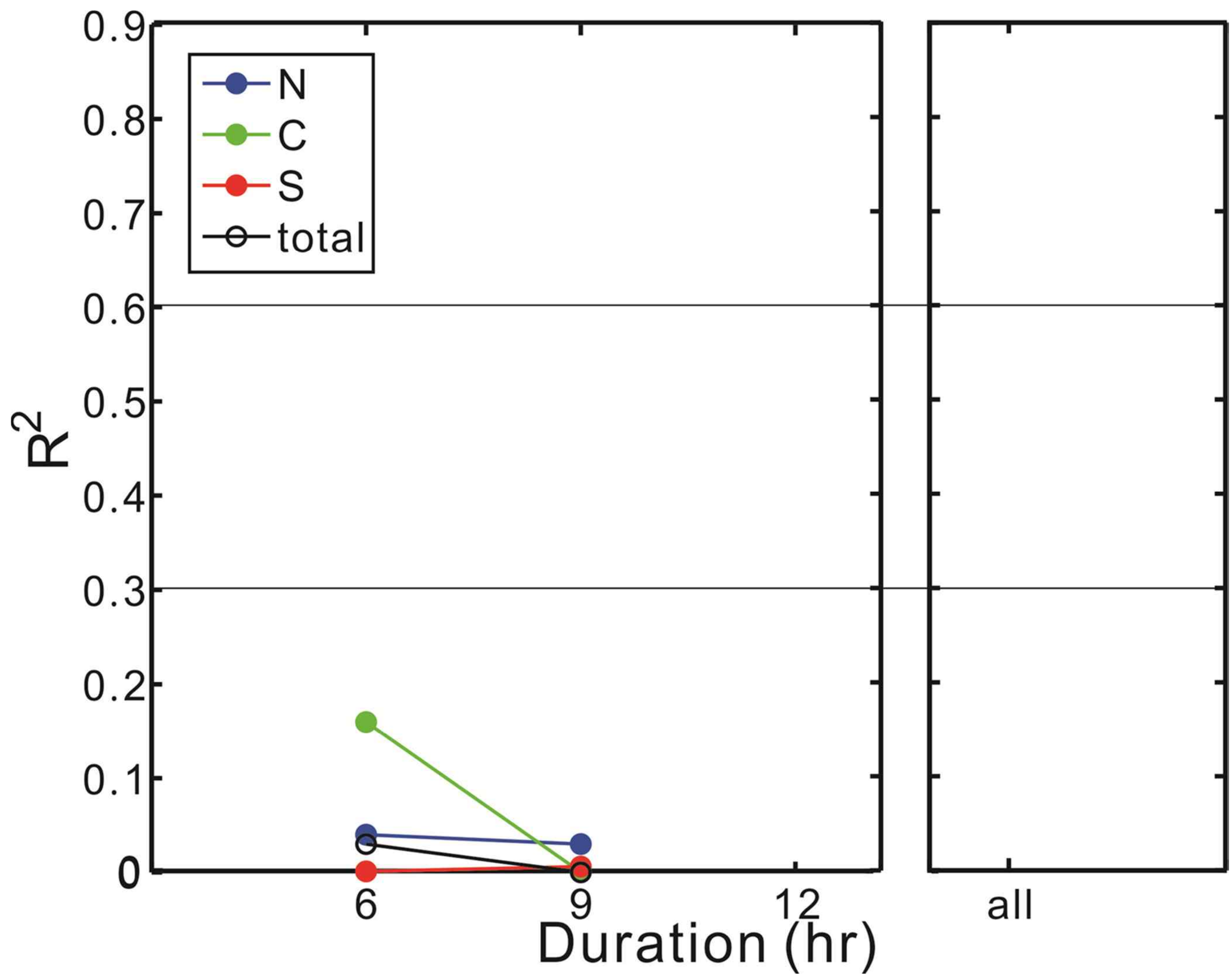
PR
Rain amount (mm)
5000
4000
3000
2000
1000
0
0
6
12
18
24
30
Duration (hr)
y=92.64x-78.8 R2=0.72


PR
Rain amount (mm)
5000
4000
3000
2000
1000
0
0
6
12
18
24
30
Duration (hr)
y=103.6x+61.98 R2=0.57

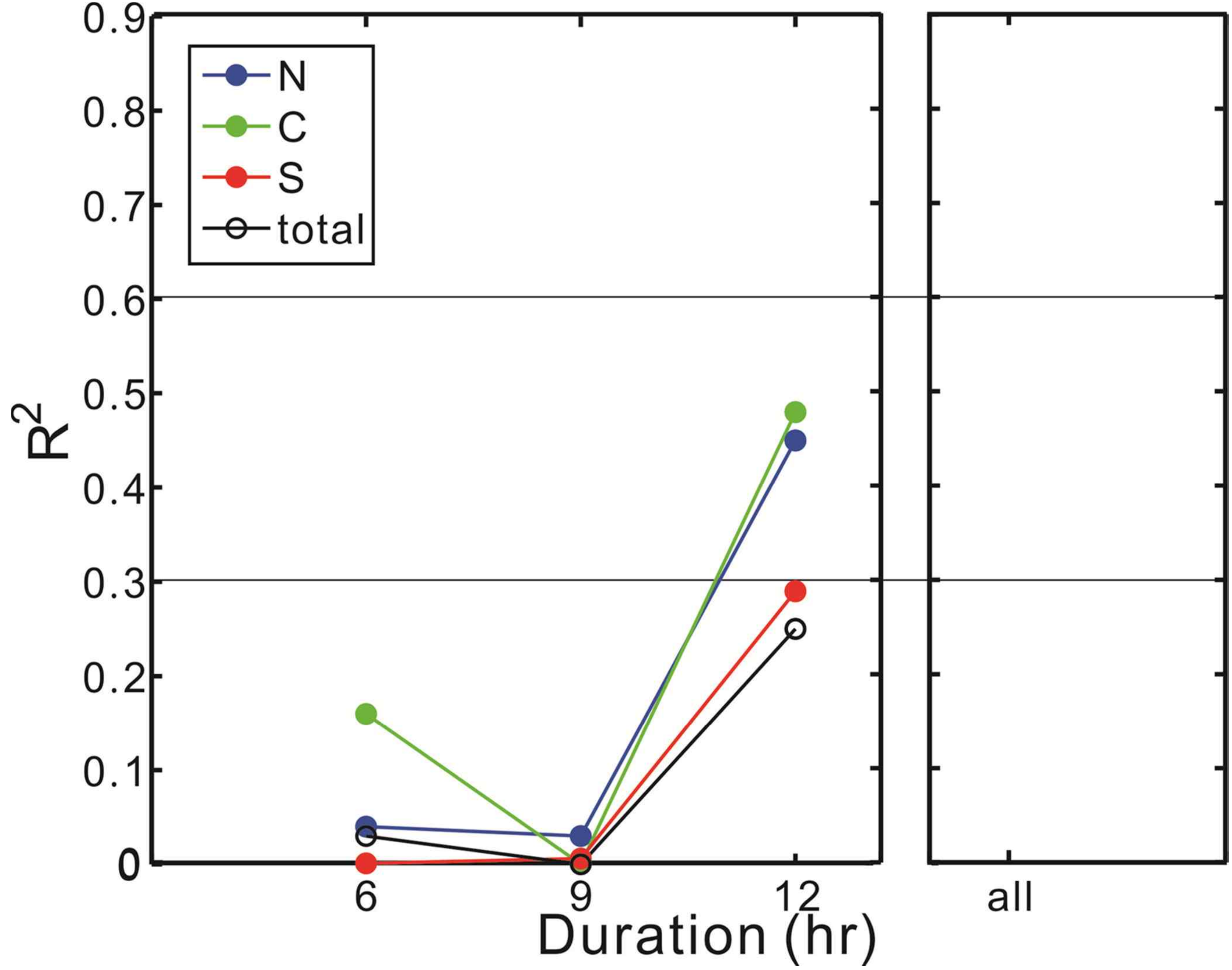

PR
y=176.2x-154.4 R2=0.64
y=103.6x+61.98 R2=0.57
y=92.64x-78.8 R2=0.72
y=52.7x+318.6 R2=0.31
Rain amount (mm)
Duration (hr)
0
1000
2000
3000
4000
5000
0
6
12
18
24
30



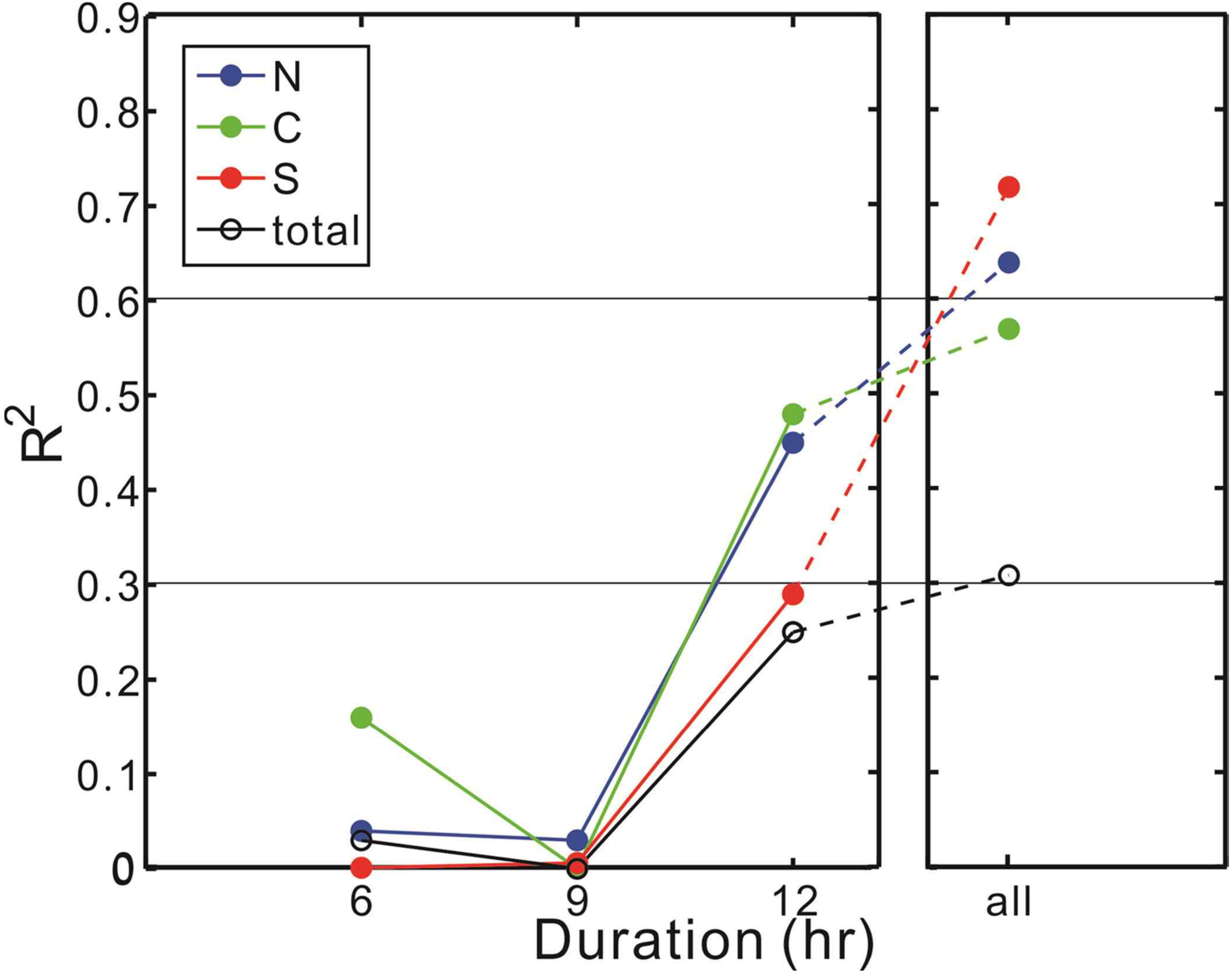
N
C
S
total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
6
9
12
all
Duration (hr)



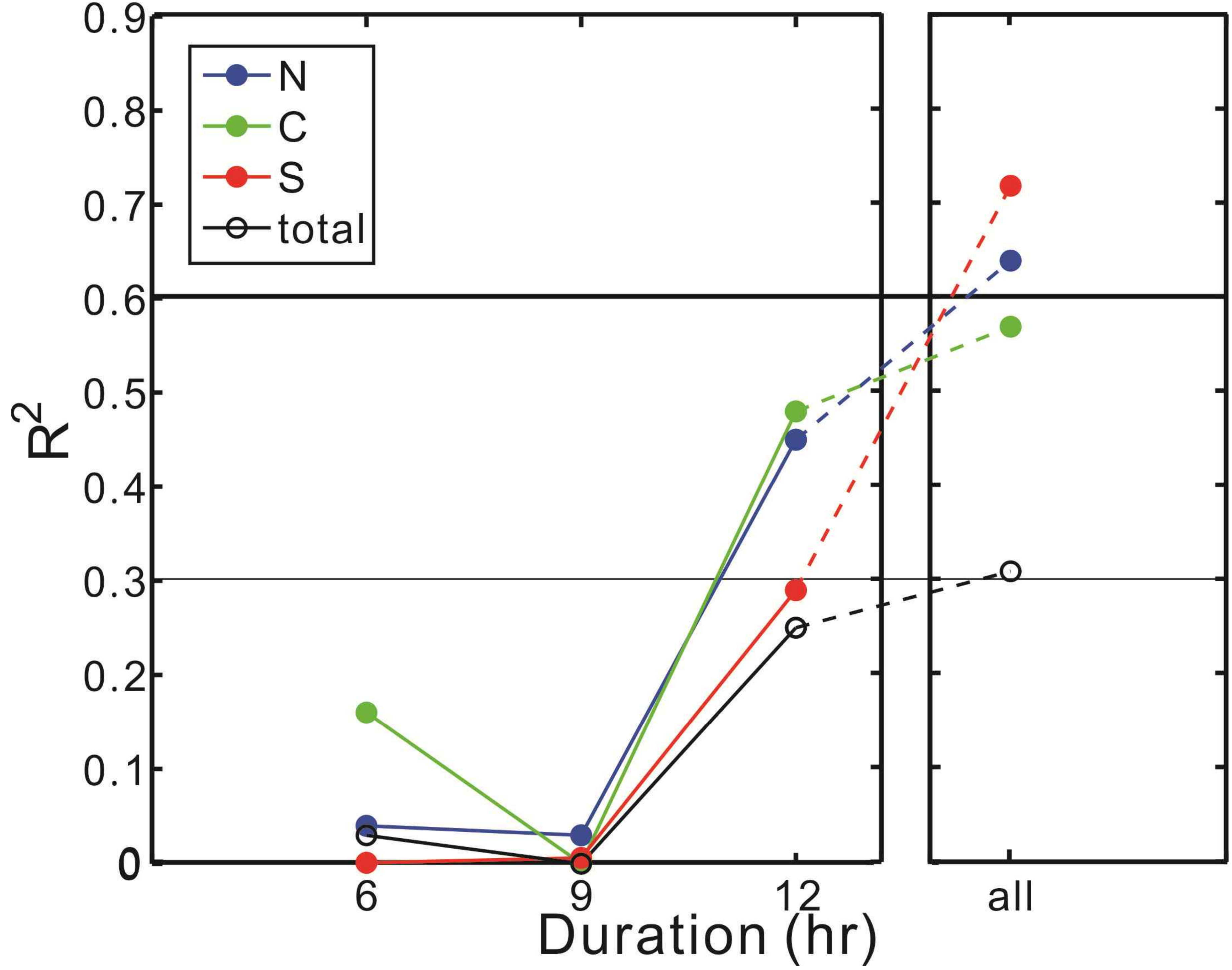
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
N
C
S
total
R2
6
9
12
all
Duration (hr)



N
C
S
total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
6
9
12
all
Duration (hr)



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
N
C
S
total
6
9
12
all
Duration (hr)

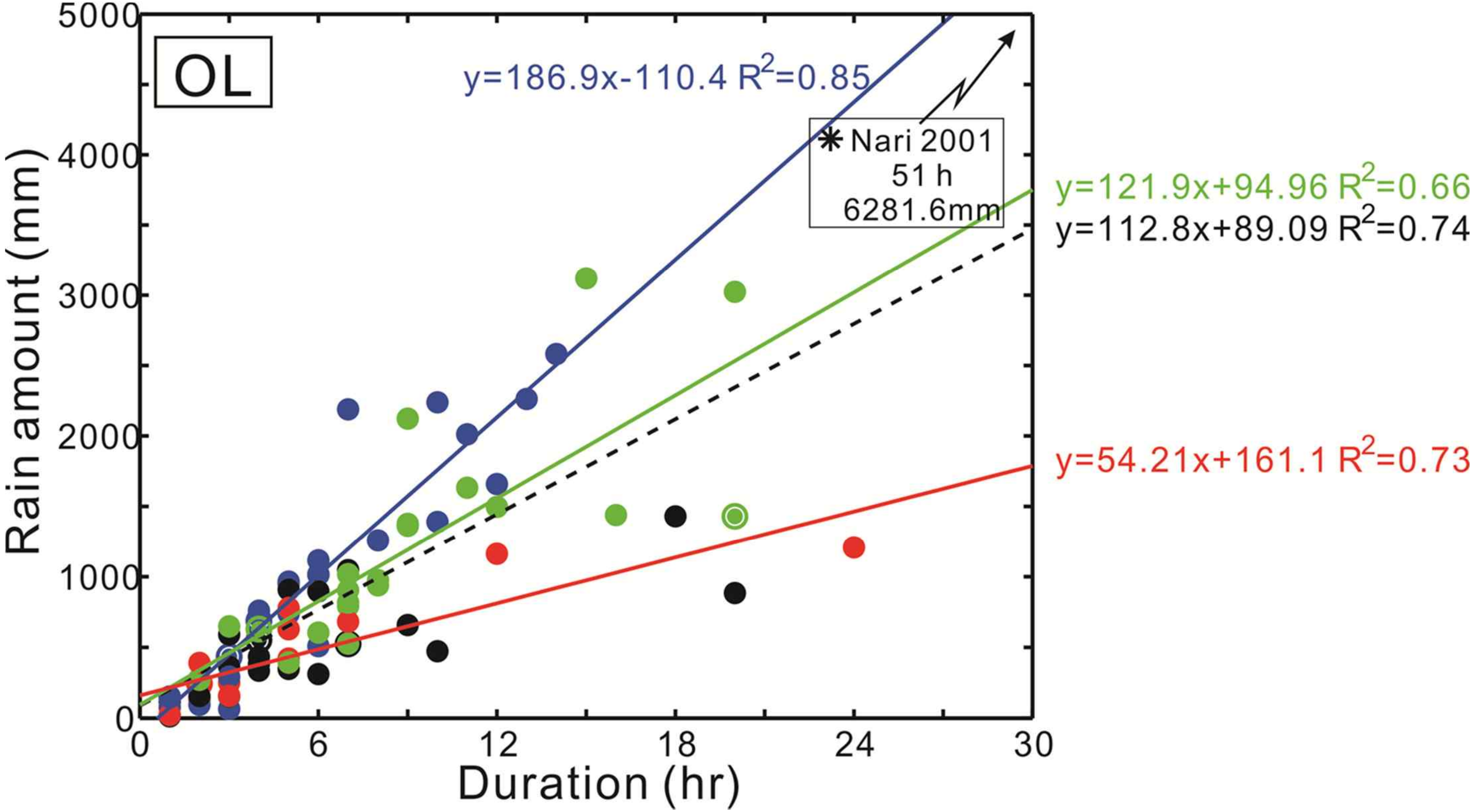


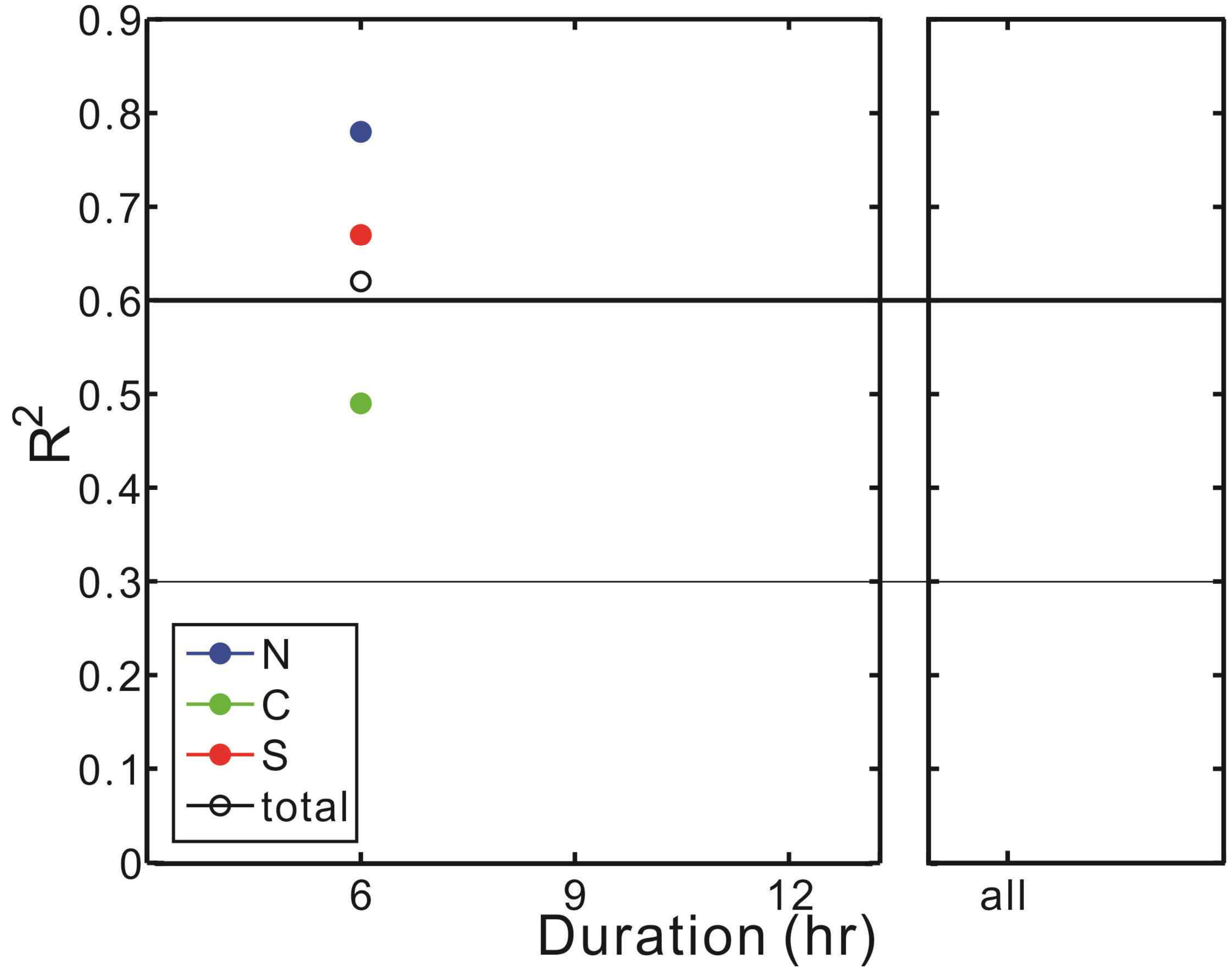
N
C
S
total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
6
9
12
all
Duration (hr)

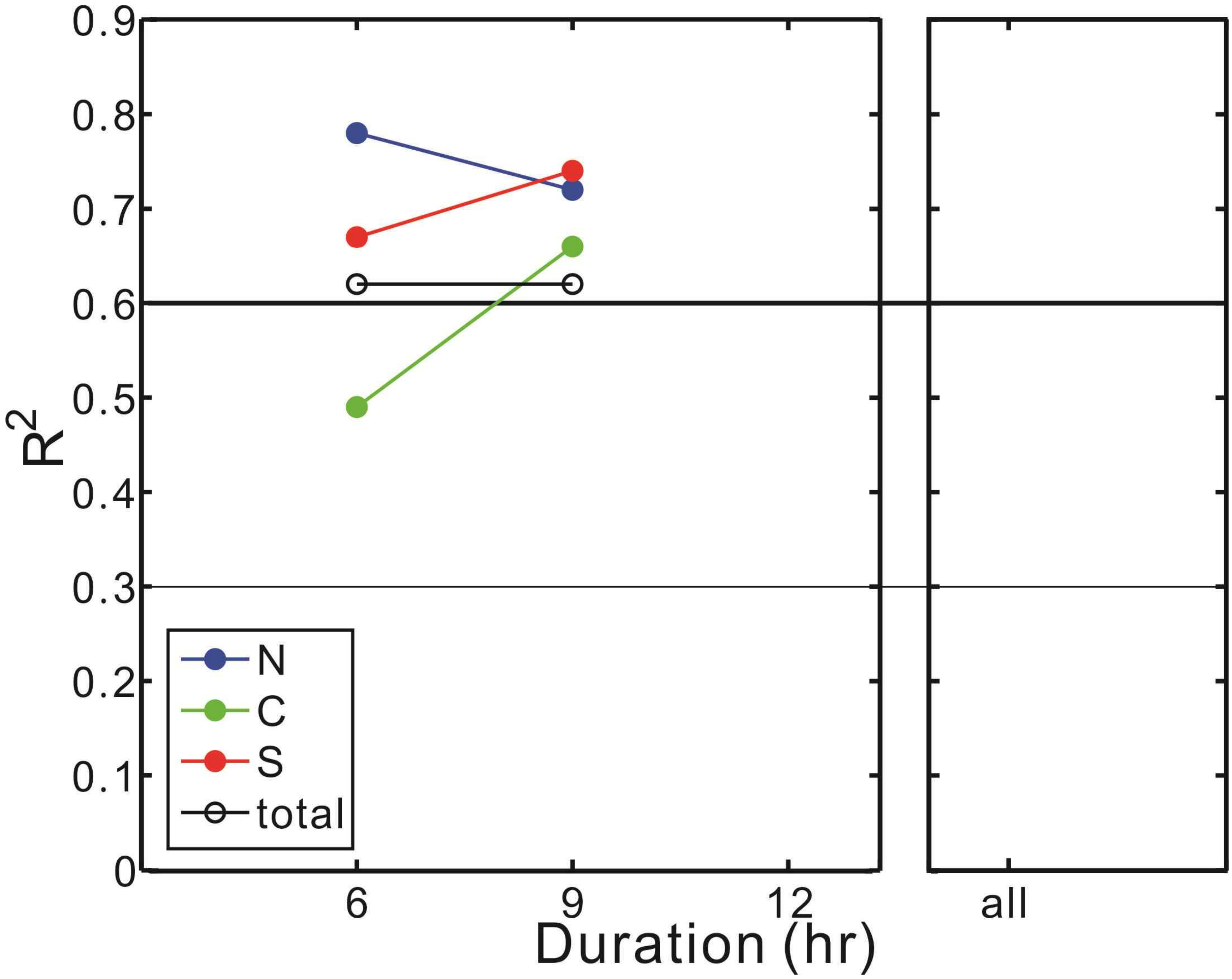
Table 2: The 12-hour rainfall intensity (mm) for the three track types during the three phases.

Phase Track Type	**PR**	**OL**	**EX**
N	1960		
C	1305		
S	1033		

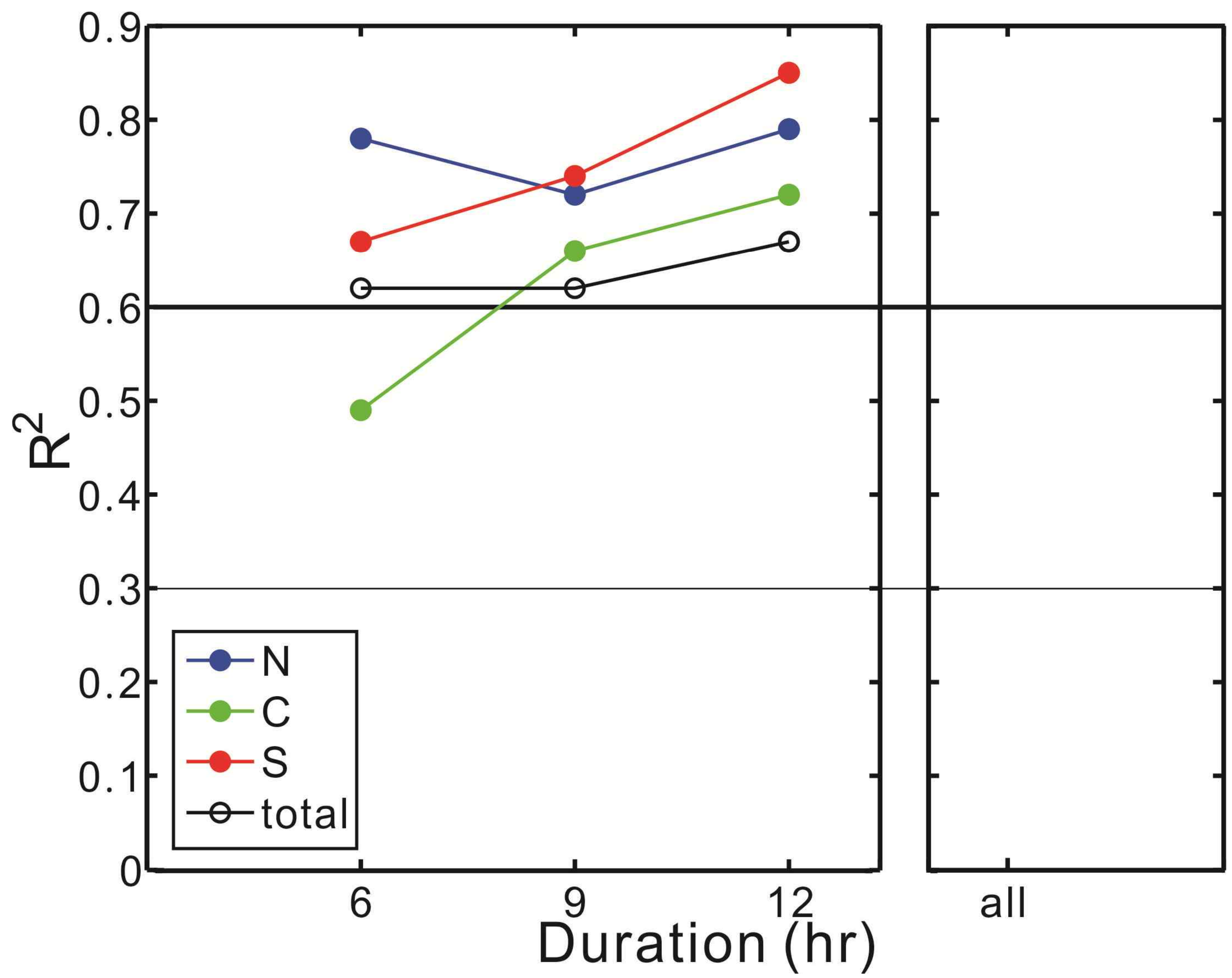
OL


OL
y=186.9x-110.4 R2=0.85
Nari 2001
51 h
6281.6mm
y=121.9x+94.96 R2=0.66
y=112.8x+89.09 R2=0.74
y=54.21x+161.1 R2=0.73
Rain amount (mm)
Duration (hr)
0
1000
2000
3000
4000
5000
0
6
12
18
24
30

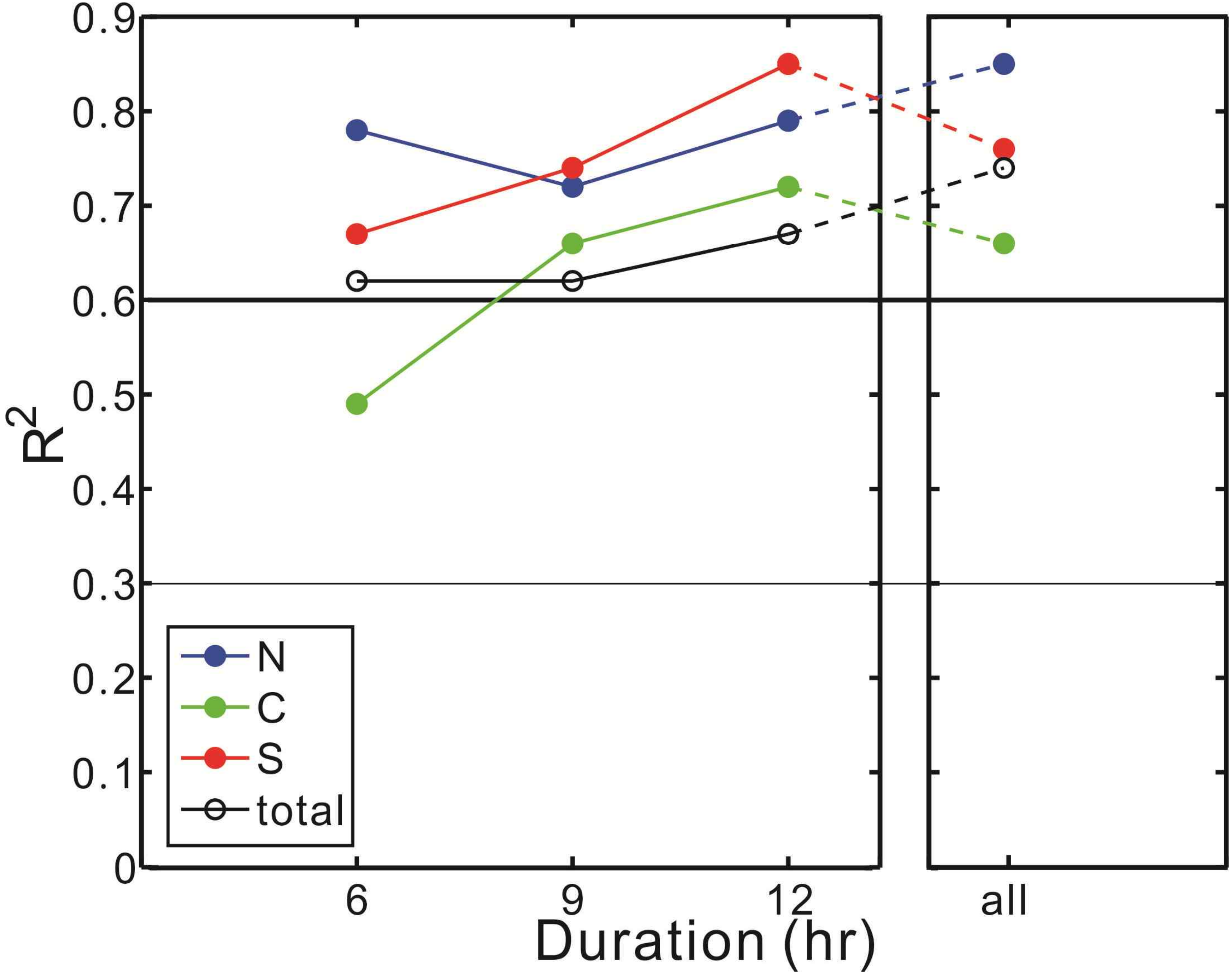

0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
N
C
S
total
6
9
12
all
Duration (hr)



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
N
C
S
total
6
9
12
all
Duration (hr)



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
N
C
S
total
6
9
12
all
Duration (hr)

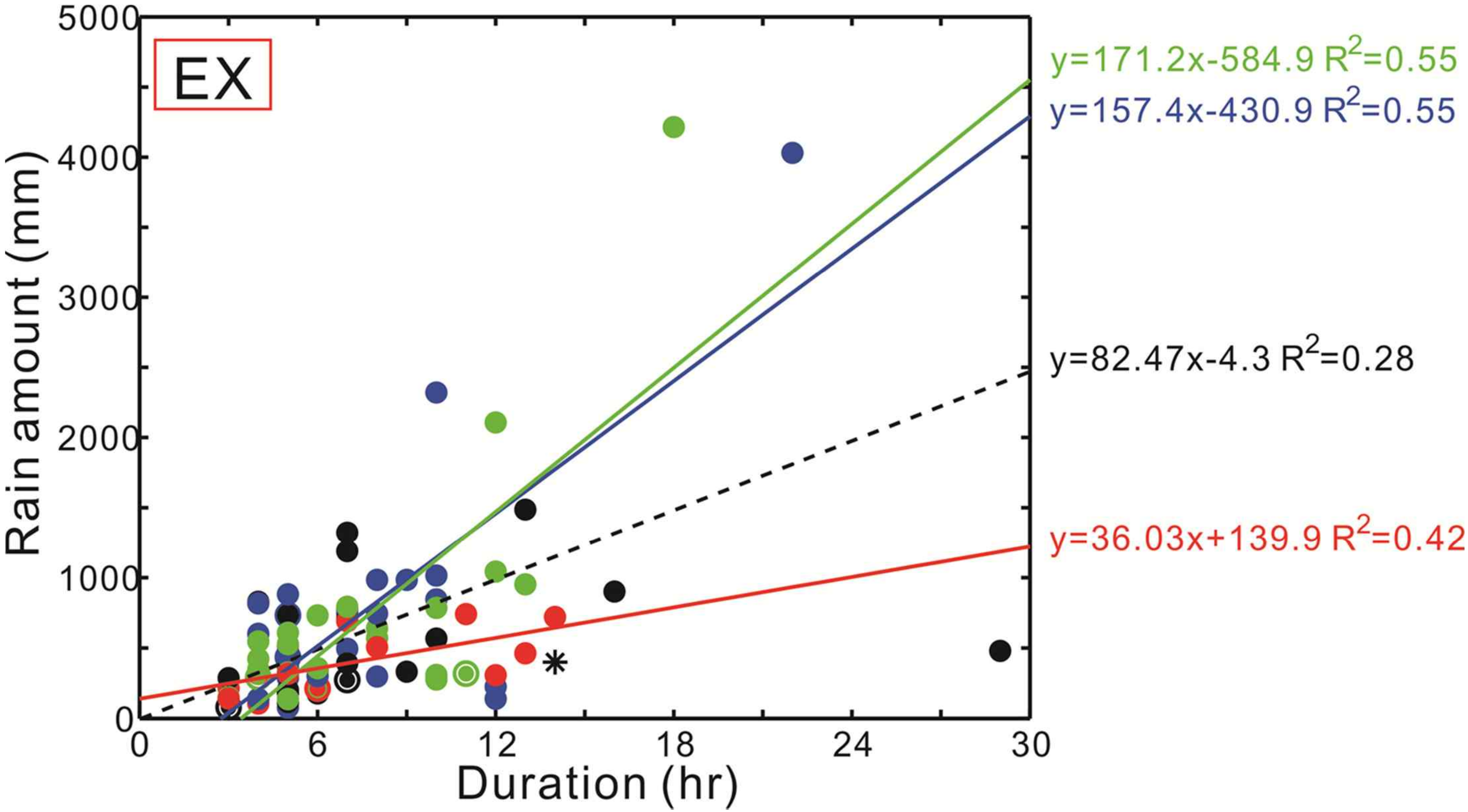


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R2
N
C
S
total
6
9
12
all
Duration (hr)

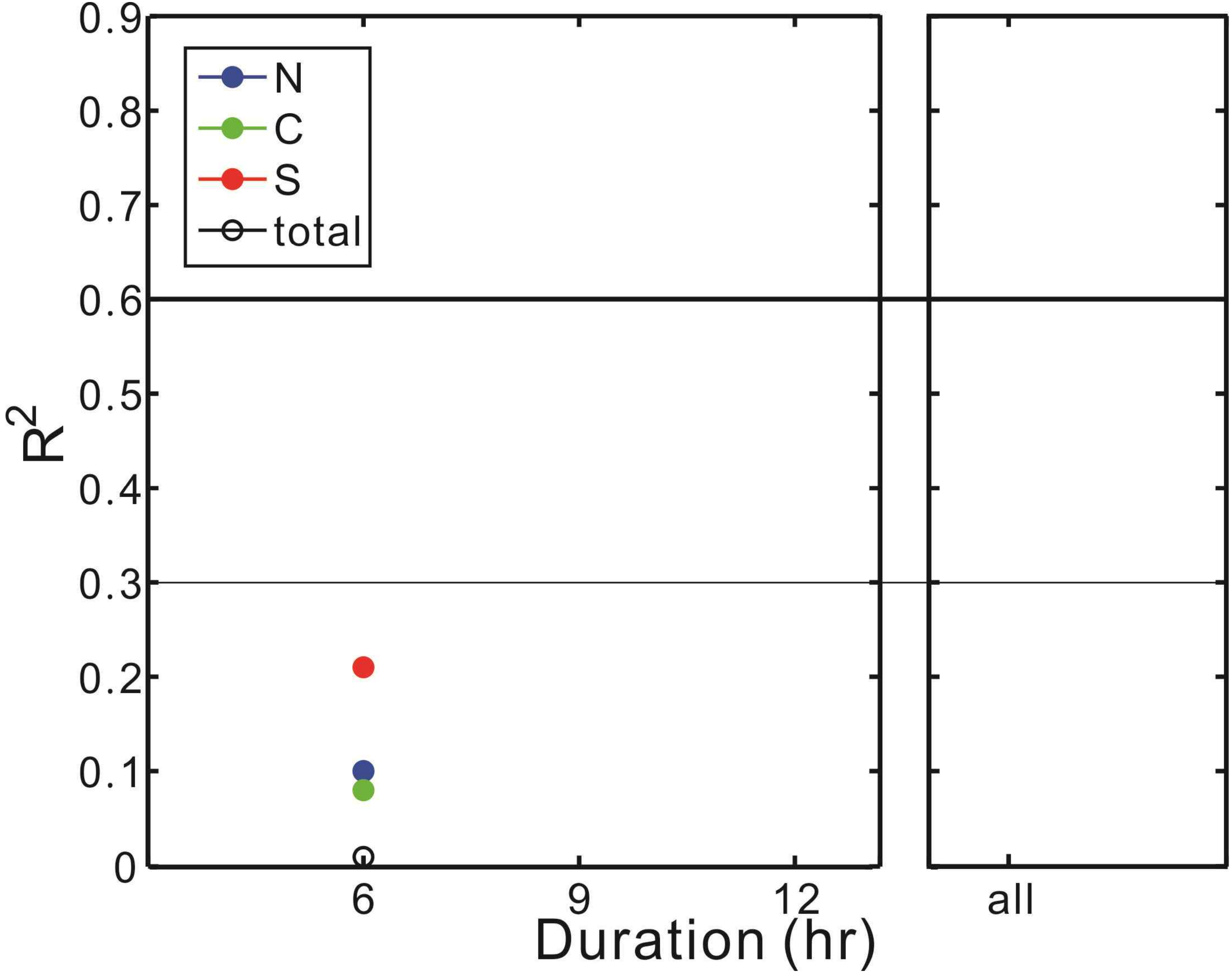
Table 2: The 12-hour rainfall intensity (mm) for the three track types during the three phases.

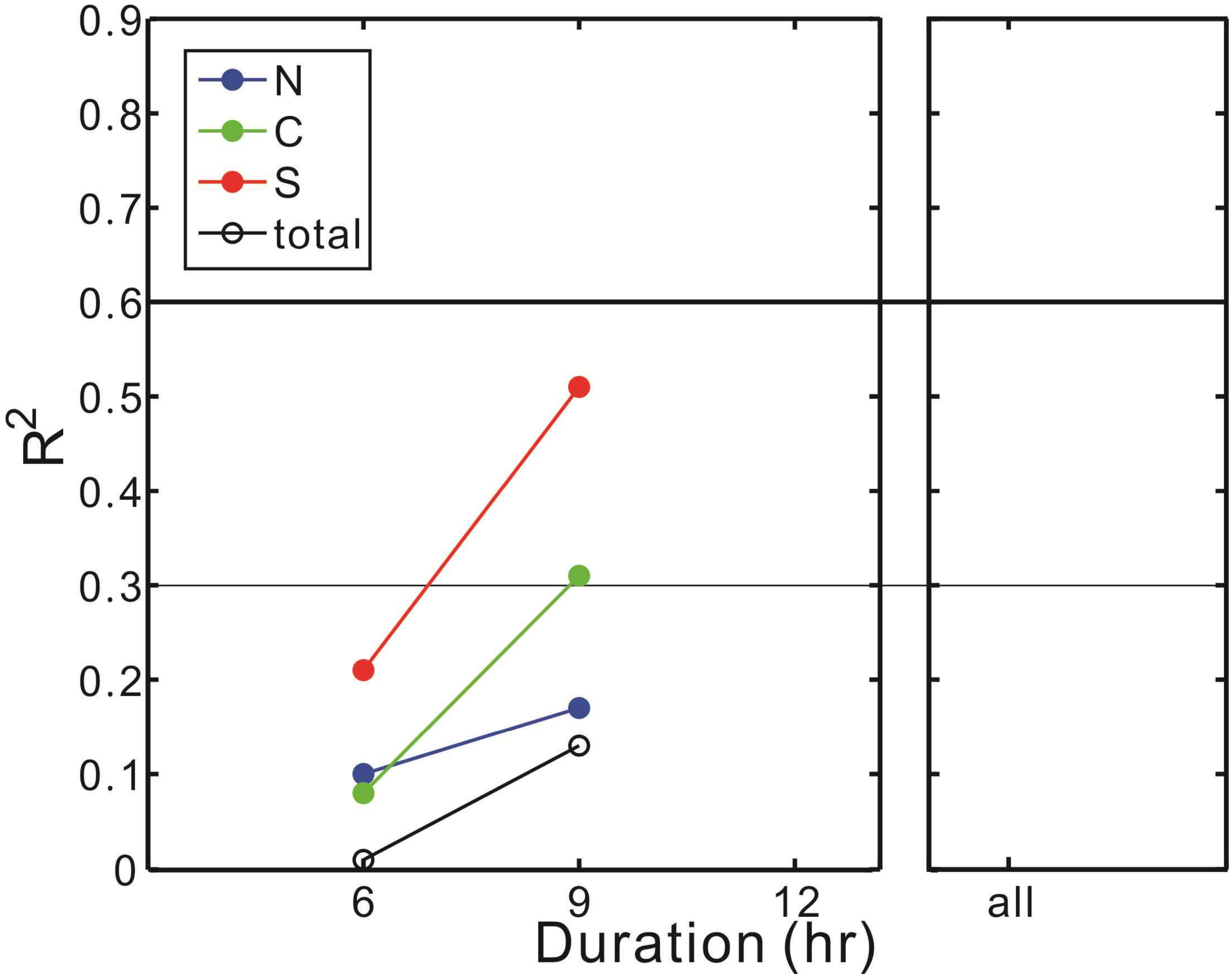
Phase / Track Type	**PR**	**OL**	**EX**
N	1960	2132	
C	1305	1558	
S	1033	812	

EX

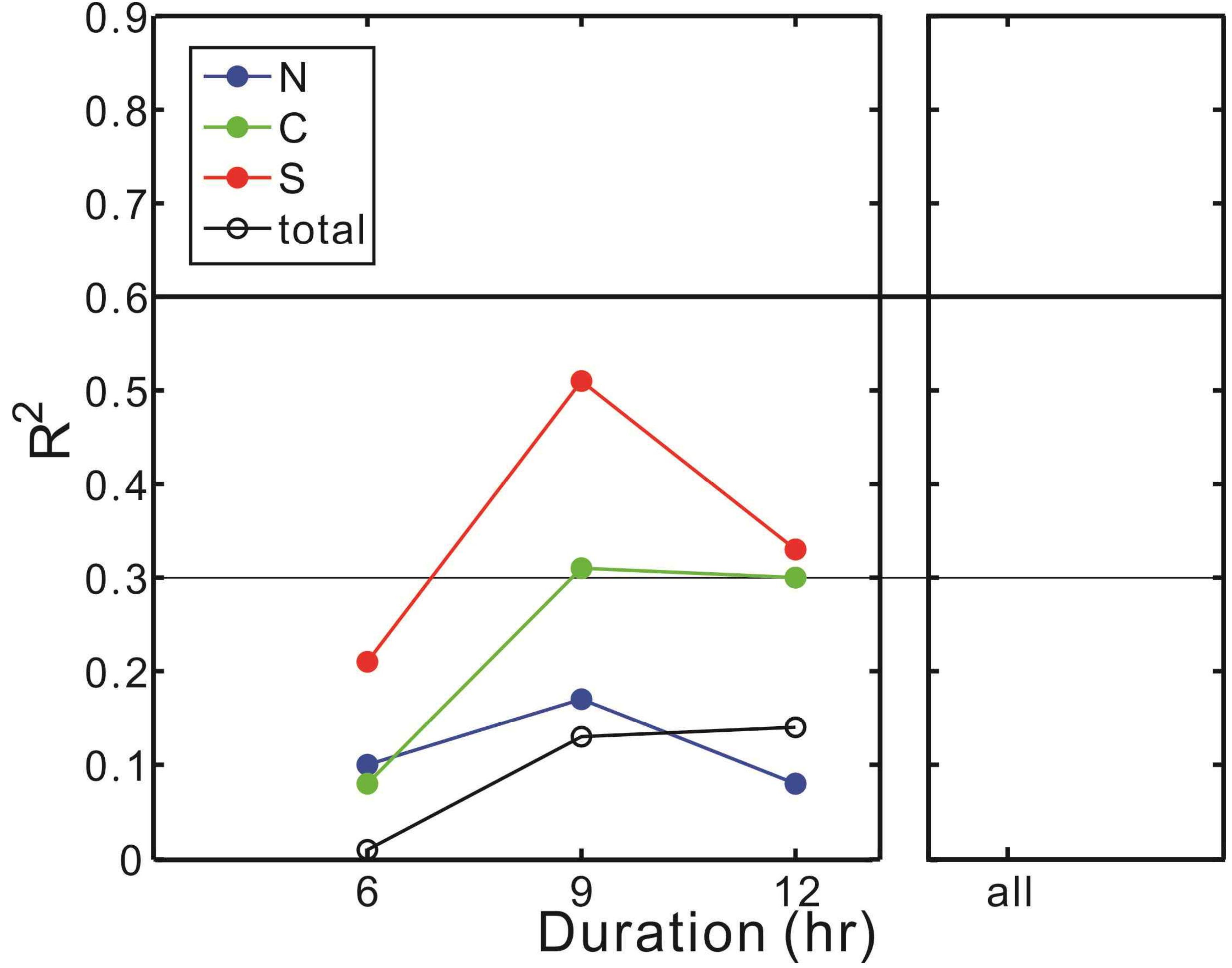


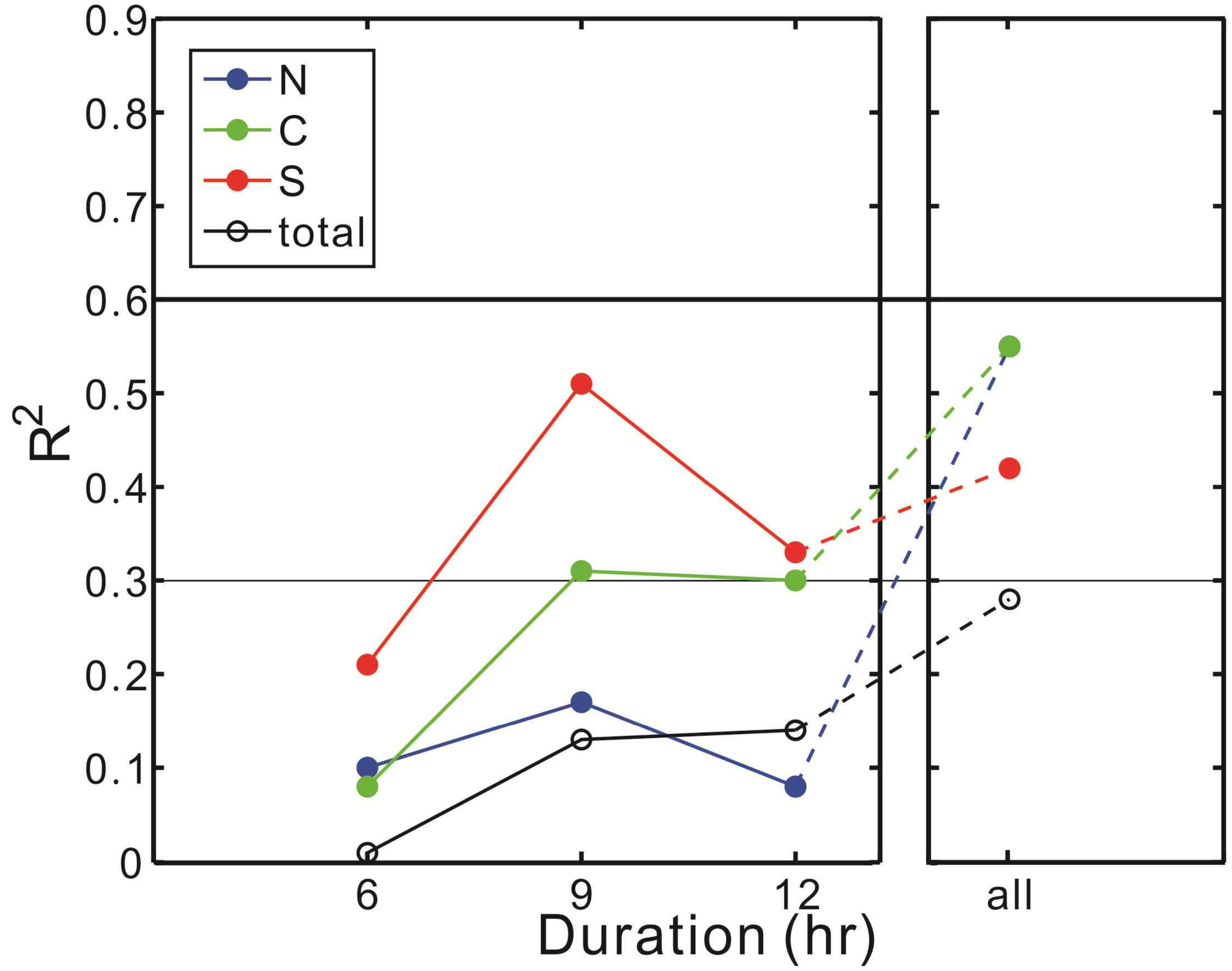
EX
Rain amount (mm)
Duration (hr)
0
1000
2000
3000
4000
5000
0
6
12
18
24
30
y=171.2x-584.9 R2=0.55
y=157.4x-430.9 R2=0.55
y=82.47x-4.3 R2=0.28
y=36.03x+139.9 R2=0.42
*


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R2
N
C
S
total
6
9
12
all
Duration (hr)



N
C
S
total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
6
9
12
all
Duration (hr)


N
C
S
total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R2
6
9
12
all
Duration (hr)


N
C
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total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R^2
6
9
12
all
Duration (hr)

Table 2: The 12-hour rainfall intensity (mm) for the three track types during the three phases.

Phase Track Type	**PR**	**OL**	**EX**
N	1960	2132	1458
C	1305	1558	1467
S	1033	812	572

Fig. 5

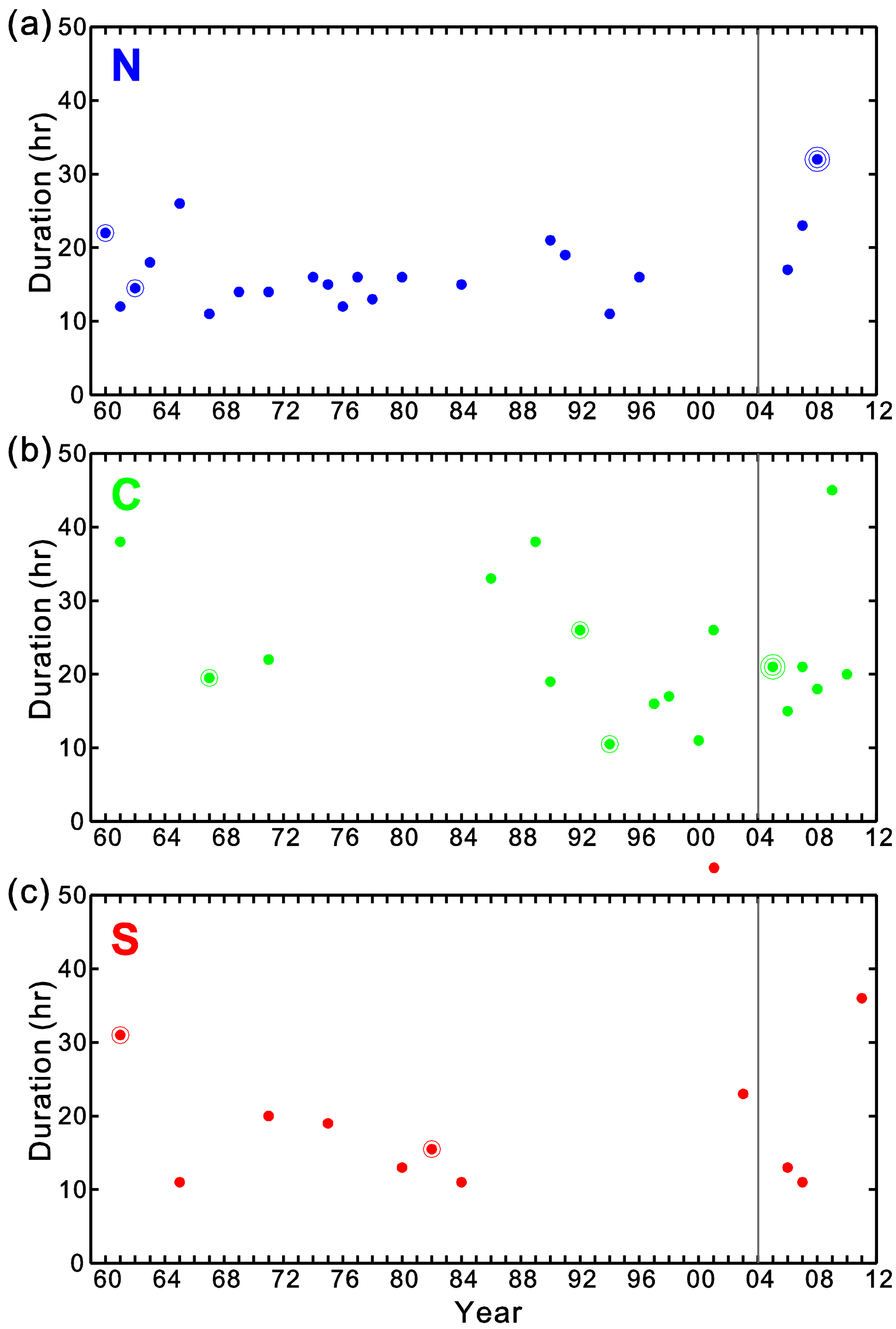


Figure 5. Time series of average duration of typhoons from 1960 to 2011 for a) north (N, blue), b) central (C, green), and c) south (S, red) track type typhoons. The thin vertical line inside each panel denotes year 2004. A dot with one circle indicates two typhoons and a dot with two circles indicate three typhoons.

Table 3: The absolute and relative (%) frequency and duration of the N, C, and S typhoons before and after 2004.

Frequency	1960-2003	2004-2011	
N	21(44.6%)	5(31.3%)	-1/3
C	15(31.9%)	8(50.0%)	+2/3
S	11(23.4%)	3(18.8%)	

Duration (hour)	1960-2003	2004-2011	
N	15.9	24.0	+1/2
C	23.9	23.3	
S	21.7	20.0	

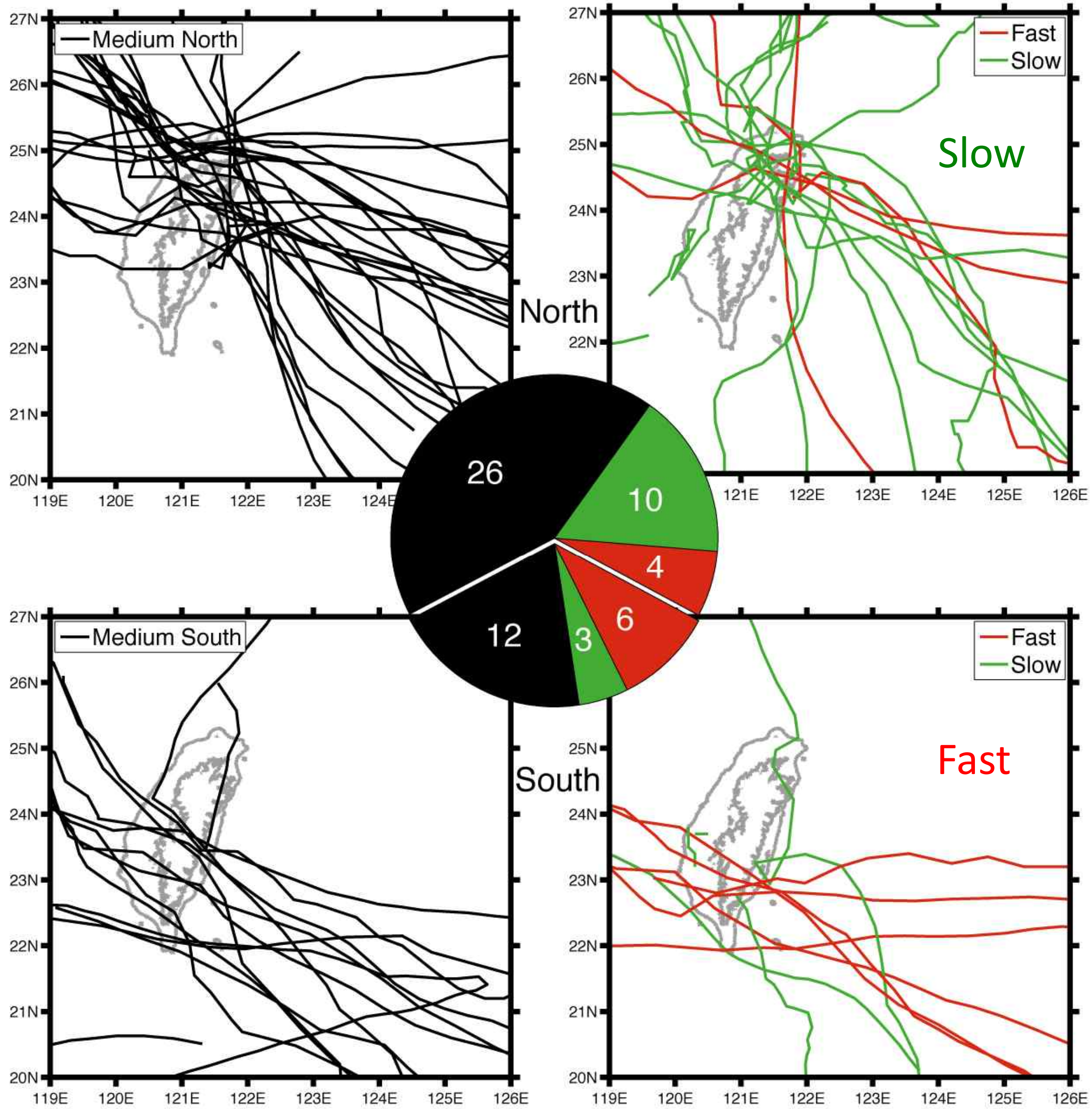
(*Chu, P.-S. et al., 2012, GRL:* Slowing trend of NCEP/NCAR and ERA-40 steering flows from 1959 – 2009.)

Total frequency +
N duration +

Table 1: The twelve typhoons in 1960-2011 with total rainfall over Taiwan exceeding 3500 mm during the three phases. The eight since 2004 are highlighted in boldface.

Rank	Year	Typhoon Name	PR	OL	EX	Total (h)	Rainfall (mm)	Track type
1	**2009**	**Morakot**	**12**	**15**	**18**	**45**	**8996**	**CWB 3 (C)**
2	2001	Nari	10	51	14	75	8108	CWB Special
3	**2008**	**Sinlaku**	**16**	**10**	**22**	**48**	**8105**	**CWB 2 (N)**
4	**2005**	**Haitang**	**11**	**9**	**12**	**32**	**5589**	**CWB 3 (C)**
5	1996	Herb	5	7	4	16	4836	CWB 2 (N)
6	1989	Sarah	5	20	13	38	4655	CWB 3 (C)
7	1960	Shirley	3	11	10	24	4637	CWB 2 (N)
8	**2007**	**Krosa**	**12**	**1**	**10**	**23**	**3936**	**CWB 2 (N)**
9	**2004**	**Mindulle**	**16**	**18**	**7**	**41**	**3856**	**CWB 6**
10	**2008**	**Jangmi**	**4**	**13**	**8**	**25**	**3800**	**CWB 2 (N)**
11	**2008**	**Kalmaegi**	**8**	**10**	**5**	**23**	**3763**	**CWB 2 (N)**
12	**2005**	**Talim**	**4**	**9**	**4**	**17**	**3526**	**CWB 3 (C)**

Asymmetric distribution of typhoon translation speed overland



Slowest group at north
Fastest group at south

Speed criteria :

61 continuous track typhoons

mean translation speed (6.2 m/s)± 1 std. (2.9 m/s)

- 77 % of slow moving storms making landfall on northern Taiwan (10/13).
- 60 % of fast cases making landfall on southern Taiwan (6/10).

(Hsu, Kuo and Fovell 2013)

Composite Rainfall

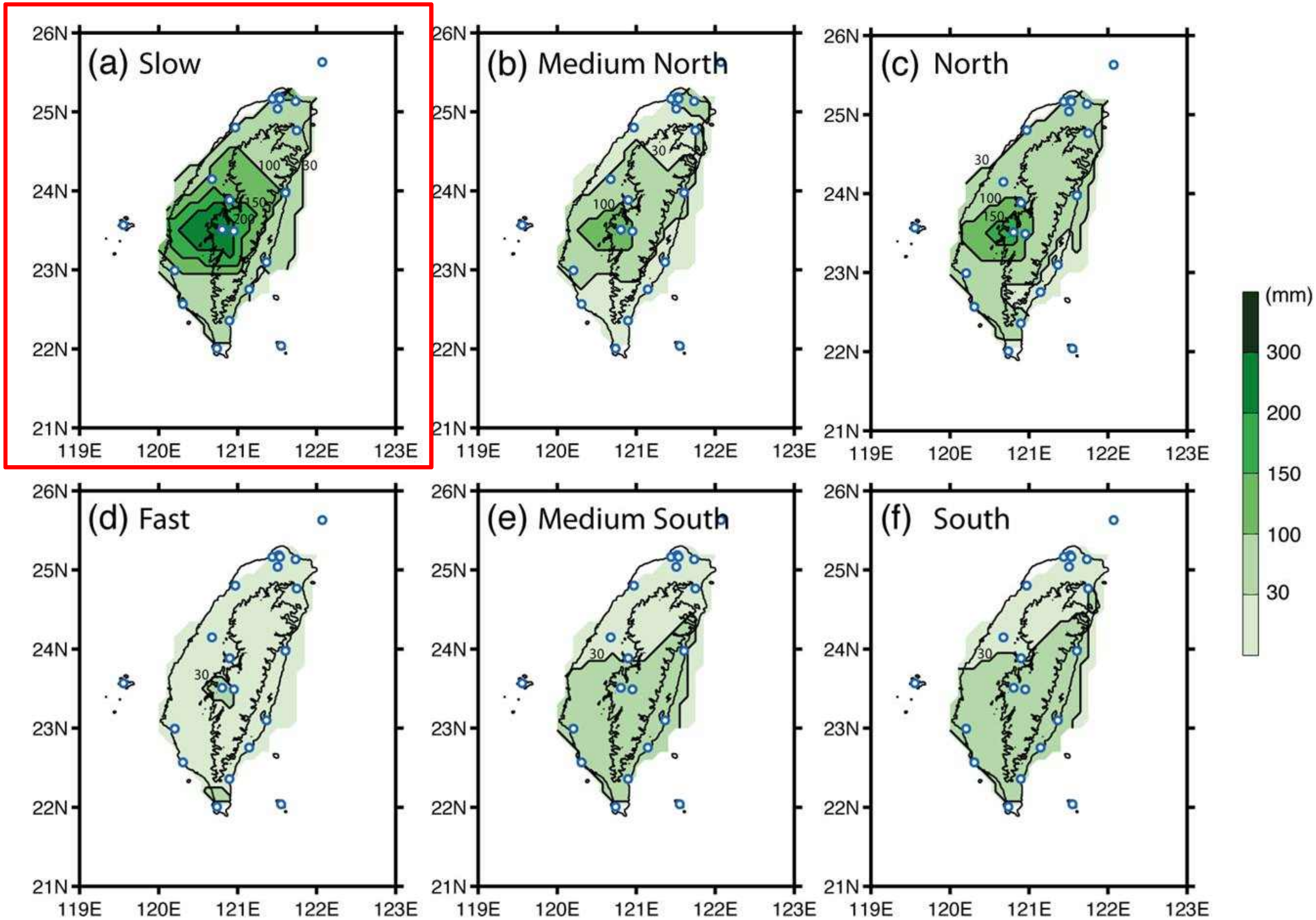


Fig 6a		
112.5	110.1	-2.1%
128.7	129.0	0.2%
78.2	92.9	18.8%
Fig. 6b		
112.2	112.1	-0.1%
128.8	130.4	1.2%
75.9	92.0	21.2%

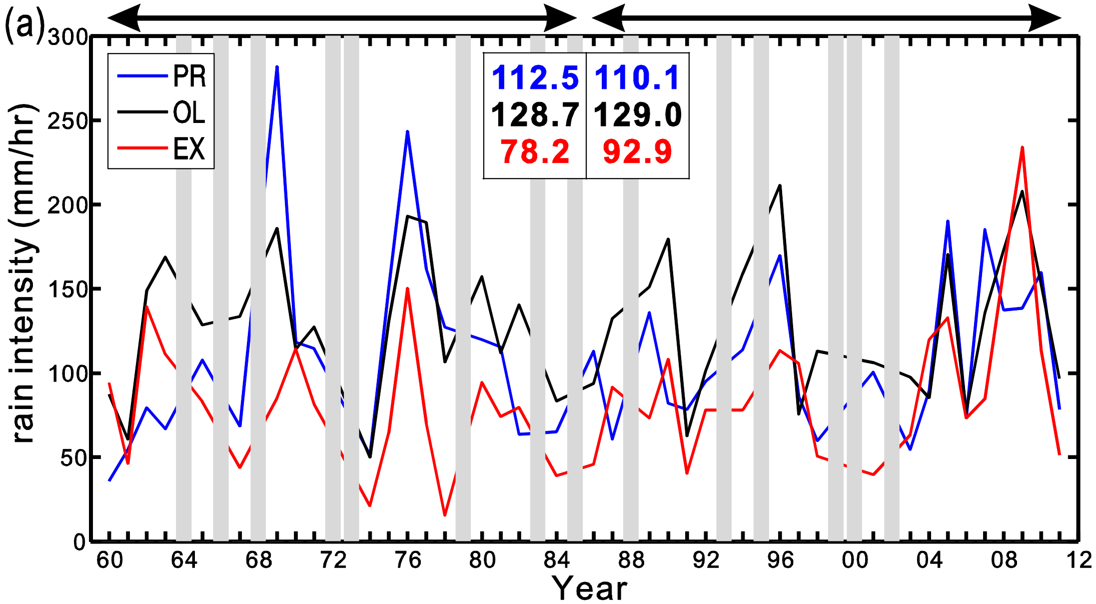
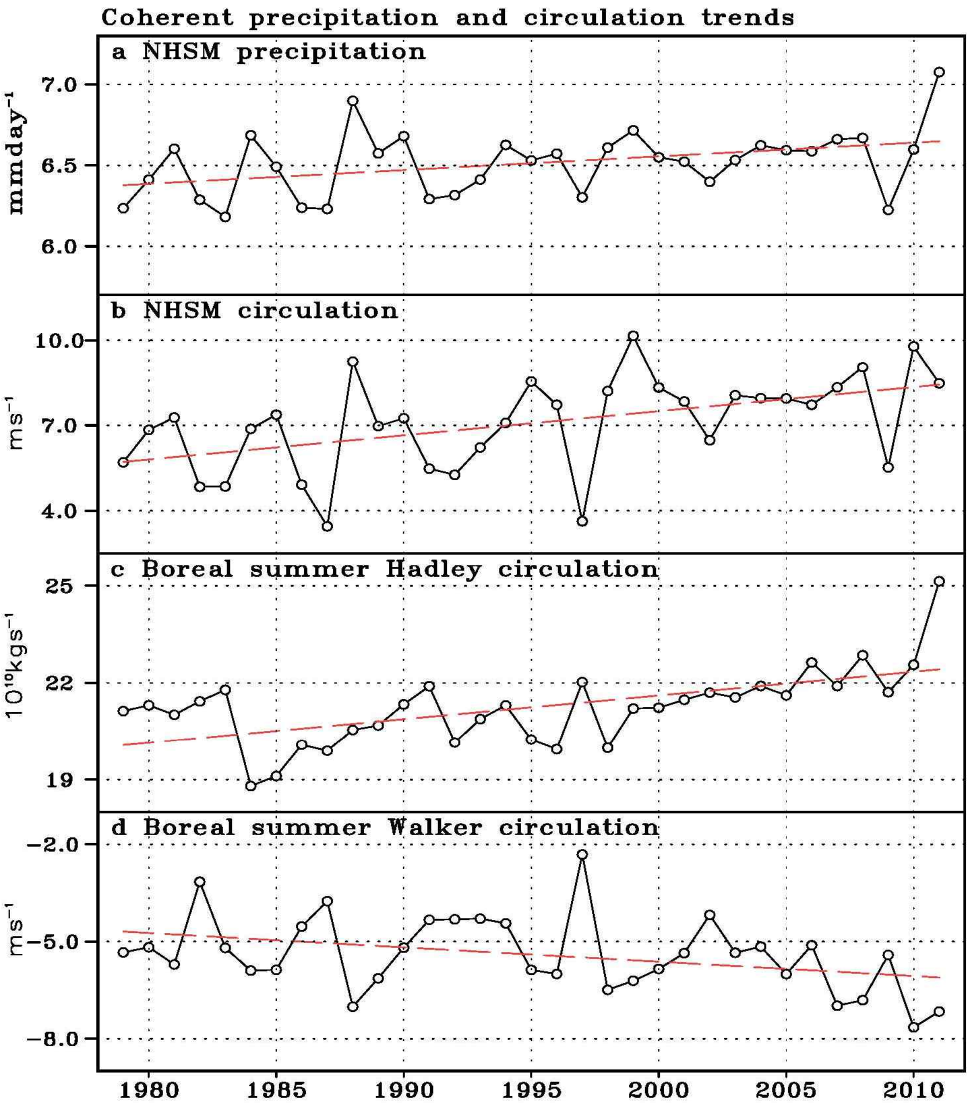


Figure 6. a) Time series of rainfall intensity from 1960 to 2011 for the pre-landing (PR, blue), overland (OL, black) and exit (EX, red) phases for weak and medium intensity (Category 1-3) typhoons. Grey vertical columns indicate years with no typhoons of the three leading track types. The table inside the panel lists the averaged yearly rainfall intensities of the three phases during the first half (1960-1985, left column) and second half (1986-2011, right column) of the 52 year period. The two sub-periods are indicated by double end arrows above the panel. b) Same as a) except strong types (Category 4-5) are included. The rainfall intensity of each strong typhoon is indicated by the respective colored dots.

Global Warming or Natural Variability?

GW predicts weakening of tropical circulations.



Strengthening of NH summer monsoon and tropical circulations consistent with slower steering flow of Taiwan TCs and enhanced monsoon interaction after TC leaves Taiwan.

(Wang et al. 2013)

Large increase in Taiwan typhoon rain intensity in 21st Century

- Mostly related to meso-α scale terrain effects : largest when center over land and smallest when exits to the Taiwan Strait.
- Within each track type rain intensity is near constant, heavier rain in recent decades mostly due to longer duration and more northern tracks.
- Increasing intensity in the last decade in the exit phase cannot be explained by the terrain effect, suggesting a decadal scale increase in the effect of monsoon-TC interactions.

Conclusions

- Pre-landfall and Over-land, the increase is due to longer duration and slight (mesoscale) change of tracks.
  – Not thermodynamic effect of global warming
- Terrain effect contributes to a false impression of climate change, yet it strongly controls the rain intensity and masks the climate change.
- After center exits Taiwan, increase due to stronger monsoon-TC interaction.
  – Not positive feedback with TC intensity (decreased over the 50 years)
  – Correlated with natural decadal variability of Mega ENSO and AMO (Wang et al. 2013)

Thank You!

侵台颱風增加只是近期→時間年代際變化。

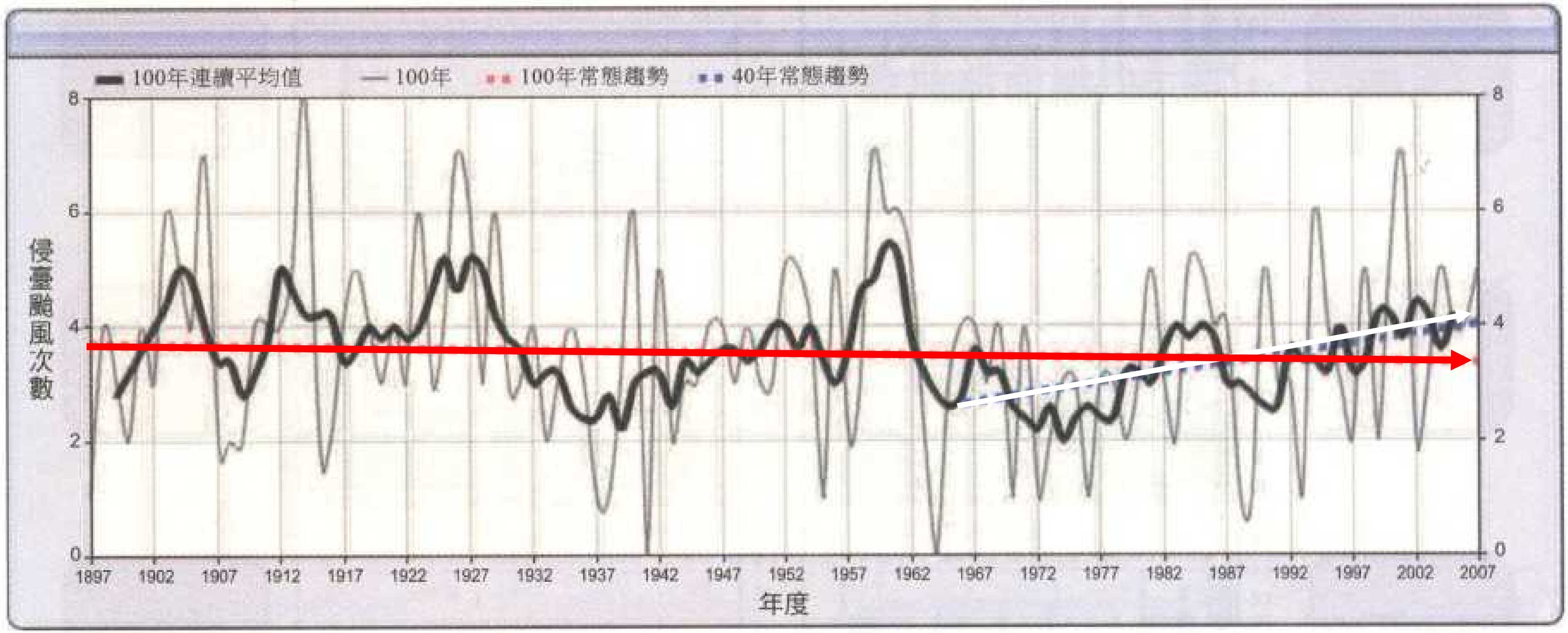


圖 2-5　臺灣地區近百年來侵臺颱風次數歷年變化圖

資料來源：李清滕、賈新興，〈颱風的長期氣候變遷〉，發表於「2008 臺灣氣候變遷」研討會（臺北：交通部中央氣象局，2008 年 8 月 25-26 日）。

Taiwan Summer TC and Extreme Rainfall – Centennial Trend

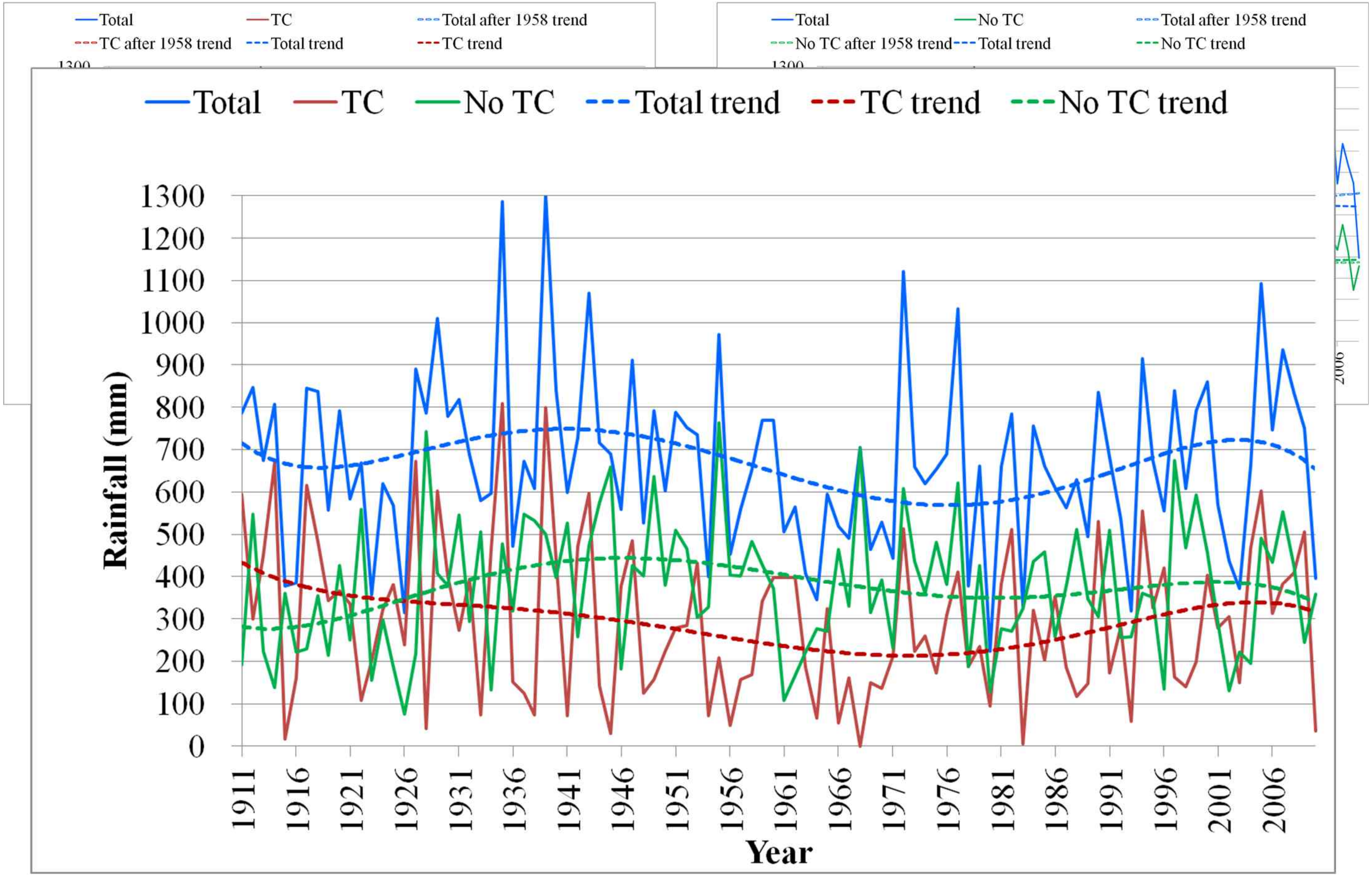
- 1911-2010; 100-years
- Six daily rainfall stations
- Typhoon rain = center within 600 km of station
- Tracks

  CWB 1958-2010

  JTWC 1945-1989

  NOAA-NCDC IBTrACS 1911-1957

Taiwan JJA 90th% (6 stations)



Summary

- Since mid-20C, China summer monsoon XRT mostly underestimated due to decreasing TC rain
  - After removing TC rain, more increase in south and less decrease in north
- A noted exception: Taiwan summer monsoon XRT hugely overestimated due to increasing TC rain
  - Caused by duration and track changes (terrain effects) and interaction with monsoon wind after TC exits.
  - Opposite to the centennial trend, but inherent monsoon XRT (~1%/decade) steady throughout the 100 years.
  - Different multidecadal variations for the TC and monsoon rainfall.

Change due to surface warming

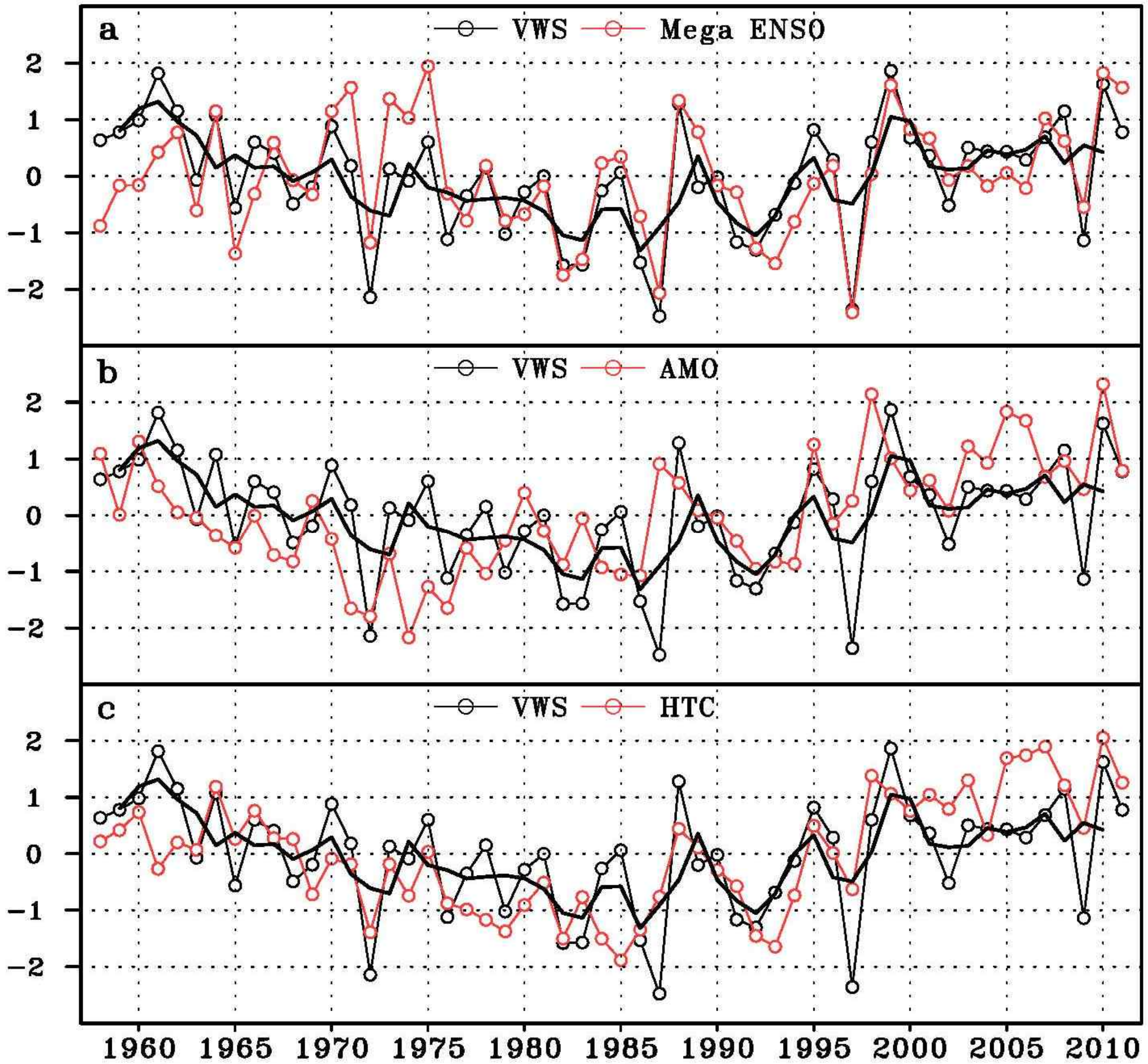
- Water vapor in the lower troposphere increases by ~7% per $^{\circ}$C (by Clausius–Clapeyron equation)
- Precipitation rate increases by ~2% per $^{\circ}$C (limited by change of raidative cooling)

  ➔ weakening of boundary layer/troposphere mass exchange of ~5% per $^{\circ}$C

  ➔weakening of tropical circulation ~5% per $^{\circ}$C

(Held and Solden 2006, Vecchi et al. 2006)

NH tropical circulation vs. multidecadal indexes



(Wang et al. 2013)