Wind and Rain in Water Balance

W. Timothy Liu, Xiaosu Xie, and Wenqing Tang

- 2 ways of surface water flux from space- complement rain in water balance & validate rain through conservation principle
- Ocean water balance
- Ocean's influence on land water balance
- Relating convergence and rain in hurricane

HYDROLOGIC BALANCE

$$\frac{\partial W}{\partial t} + \nabla \bullet \Theta = E - P$$

$$\Theta = \frac{1}{g}\int_0^{p0} qU\mathbf{d}p$$

$$W = \frac{1}{g}\int_0^{p0} q\mathbf{dp}$$

Two ways of estimating air-sea water flux- can they be reconciled?

- Traditional: Evaporation and precipitation separately - “supply side”
- New: As the divergence of moisture transport – “demand side”
- Evaporation is transported by turbulence. At small scale of turbulence, factors of atmospheric circulations, such as, Coriolis force, pressure gradient force, baroclincity, cloud entrainment, are not important
- Integrated moisture transport is less sensitive to small-scale ocean processes reflected in surface current shear and temperature gradient that control turbulence.

Bulk parameterization

- Bulk parameterization was first used as a zero order approximation of what we wanted from what we had: bulk measurements. We hided our ignorance or incapability in the coefficient and we need to understand its limit.

$$E = \rho C_E (u - u_s)(q_s - q)$$

- We could measure u, T_s (q_s), but not q from space. But we could measure W – we demonstrated to get q from W in 1982, and q from radiances recently
- u, q_s, and q are derived from brightness temperature, and we should be able to retrieve E from brightness temperature. Bypass uncertainties of CE and multiplying of U and q errors

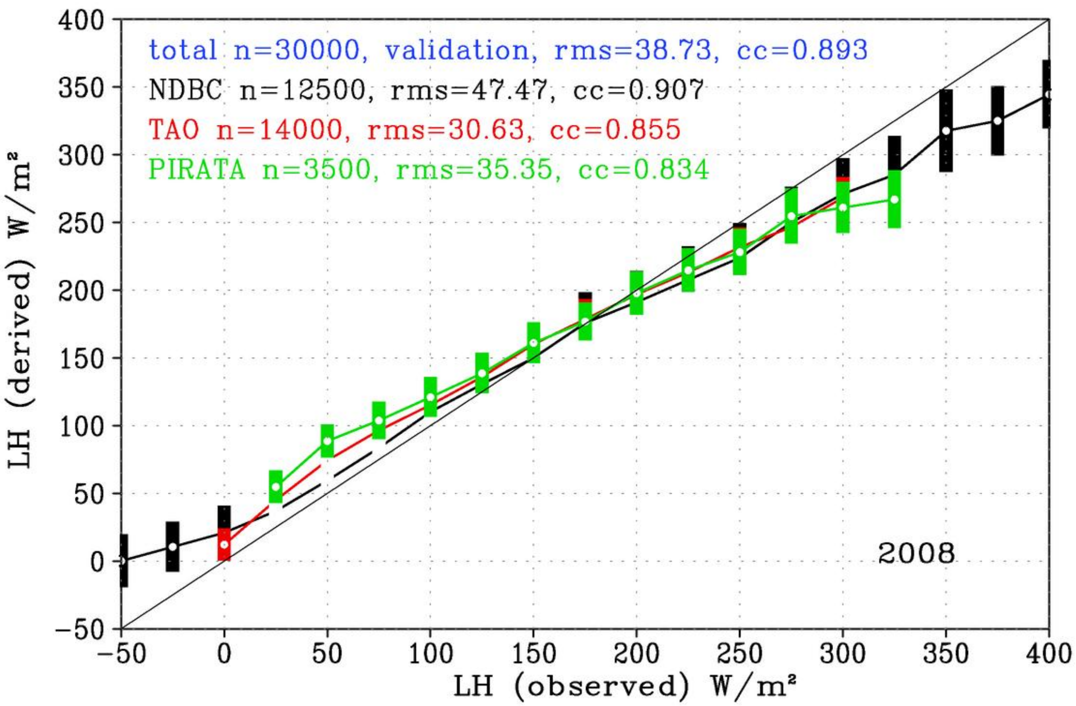
Table 1. Available data sets of surface turbulent fluxes

Data	GSSTF	J-OFURO	HOAPS-3	OAFLUX
Geographical area	global ocean	global ocean	global ocean	global ocean
Time coverage	07/1987-12/2000	01/1988-12/2006	07/1987-12/2005	01/1985-03/2010
Spatial resolution	1x1 degree	1x1 degree	0.5x0.5 deg	1x1 deg
Frequency	daily, monthly	daily, monthly	5 day, monthly	daily, monthly
Data source	SSM/I, NCEP SST	SSM/I, NCEP OISST	SSM/I, AVHRR	SSM/I. NCEP, ECMWF
Methodology	bulk formula	bulk formula	bulk formula	bulk formula
Insti./Investigator	GSFC/Chou	Tokai Univ./ Kubota	Univ. of Hamburg/Schultz	WHOI/Yu

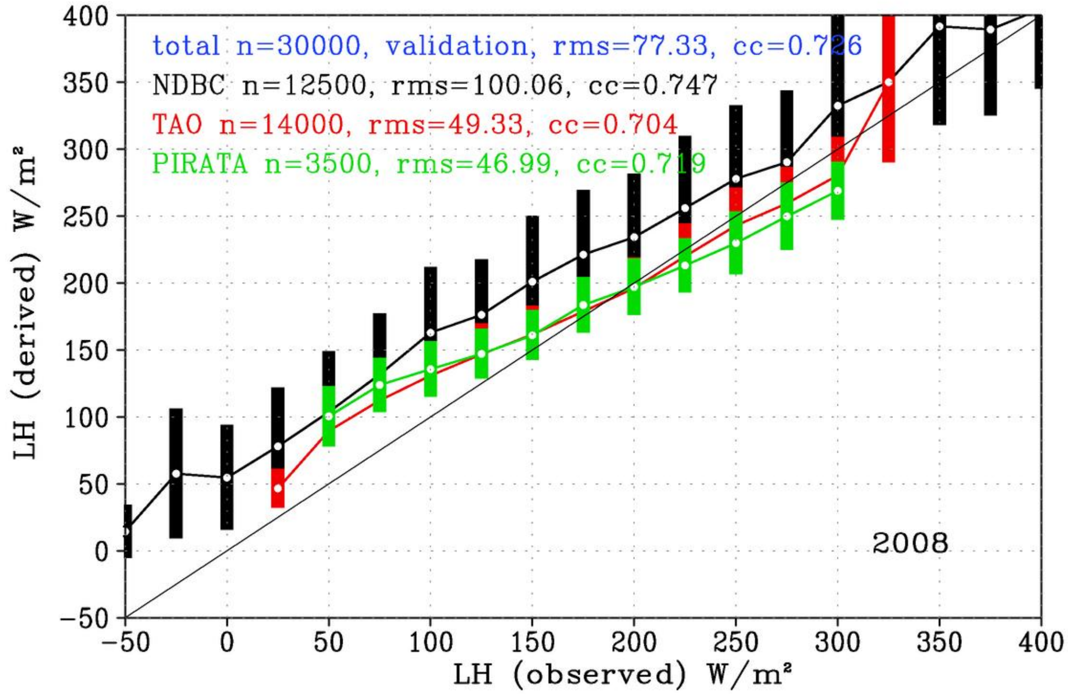
Bourras (2006) compared 5 satellite E with 3 sets of buoy data. Coincident space data and TAO buoy for 3 year monthly means give bias of 10-49 W/m^2, RMS differenceof 24-41 W/m^2

Smith et al. (2010) compared 9 sets of E. Regional differences could be 40 W/m^2 for a 9 year mean.

Santorelli et al. (2011) compared the IFREMER & OAFLUX E data in the Atlantic.
Annual mean differences: ~16 W/m^2 in tropics
~60 W/m^2 off Brazilian coast
~40 W/m^2 off South African coast & Gulf Stream
RMS differences : ~40 W/m^2 in Gulf Stream and coastal regions
10-30 W/m^2 in most of the Atlantic Ocean



LH (Direct)
N=30,000
RMS=38.73
CC=0.893



LH (Bulk)
N=30,000
RMS=77.33
CC=0.726

HYDROLOGIC BALANCE

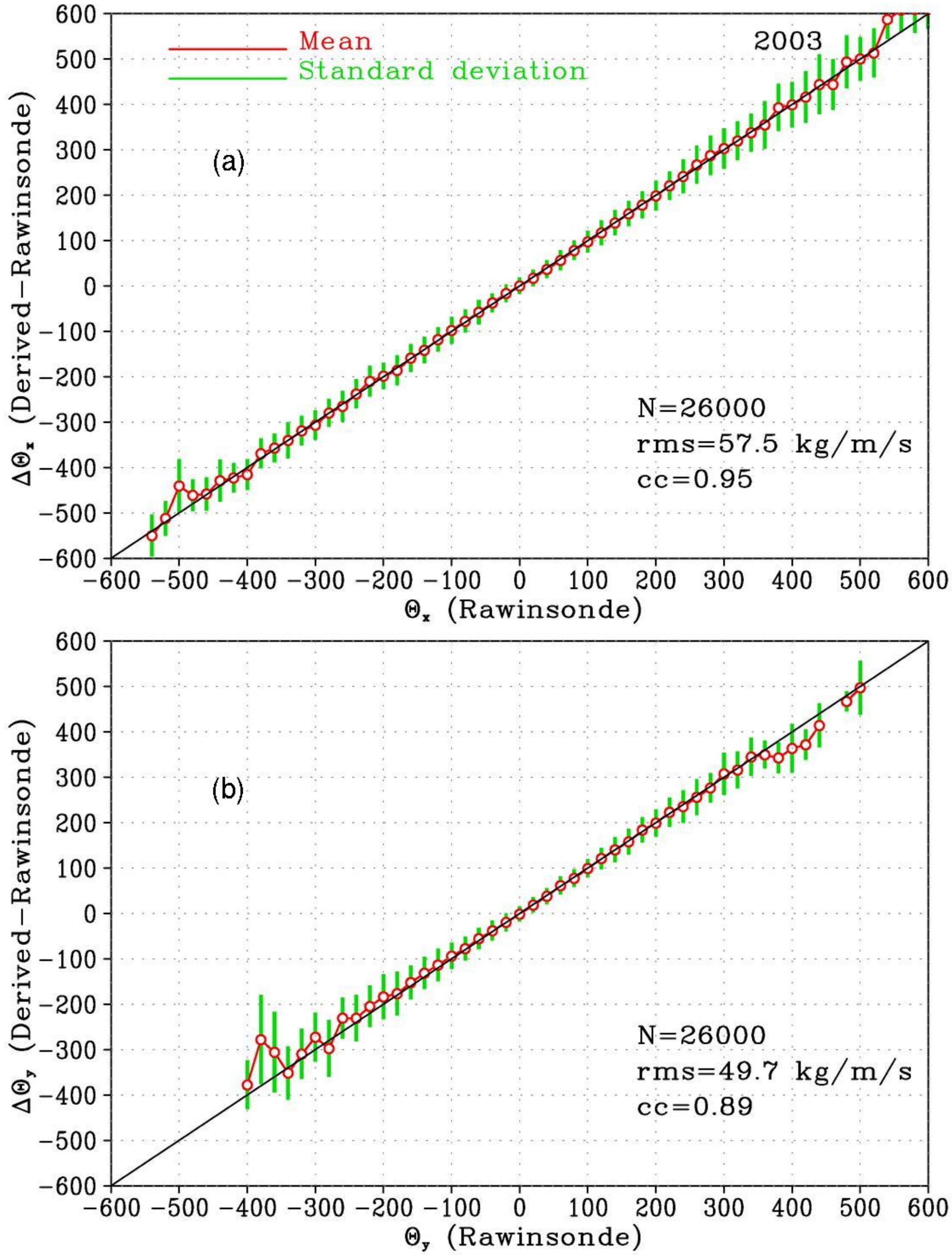
$$\frac{\partial W}{\partial t} + \nabla \bullet \Theta = E - P$$

$$\Theta = \frac{1}{g}\int_0^{p0} qU\mathbf{d}p$$

$$W = \frac{1}{g}\int_0^{p0} q\mathbf{dp}$$

$$\Theta = \mathbf{Ue}\, W$$

Θ is equivalent to column water vapor W advected by Ue.
Ue is the depth-averaged wind weighted by humidity
We use SVR to relate Ue to wind at two levels:
1. U_N: scatterometer surface wind stress
2. U_{850mb}: cloud drift wind (free-stream wind)



Θ_x

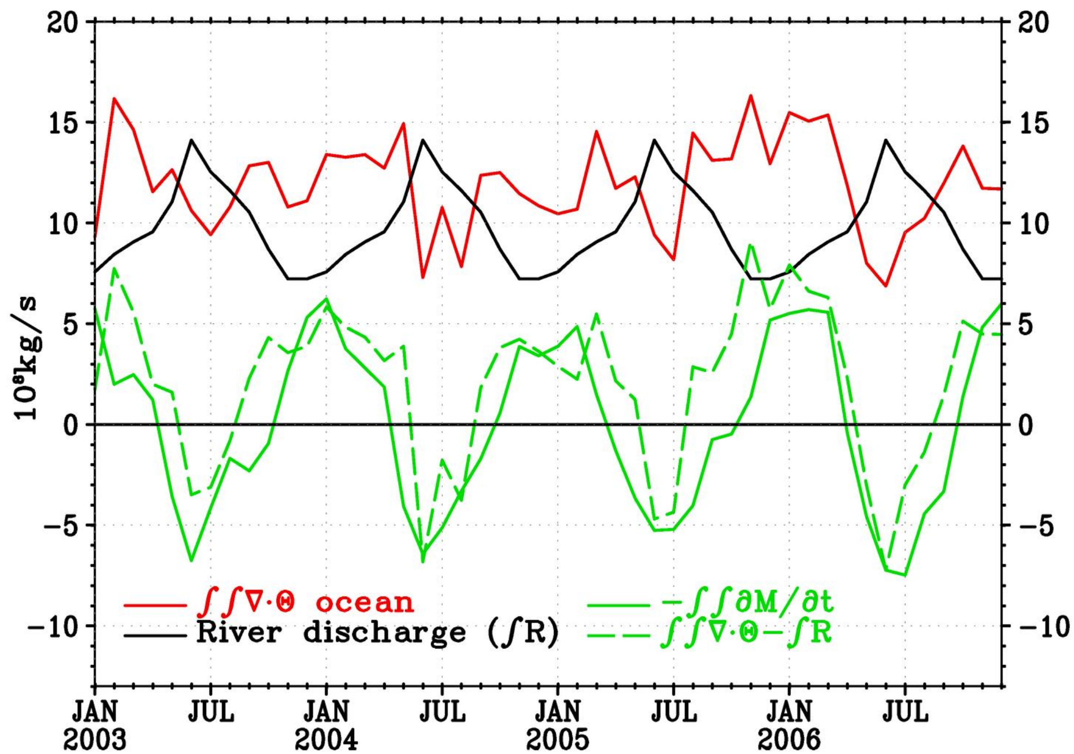
N=26,000
rms=57.5 kg/m/s
CC=0.95

Θ_y

N=26,000
rms=49.7 kg/m/s
CC=0.89

Ocean Balance

Global Ocean Water Balance



$$\iint \frac{\partial M}{\partial t} = \int R - \iint \nabla \cdot \Theta$$

GRACE Dai/Trenberth Liu/Xie

$$\iint (E-P) = \int \Theta = \iint \nabla \cdot \Theta$$

Four-year means in cm/yr

div of water transport

Liu (2010) 10.6

E-P

Merra (2008) 10.6

NEWS 10

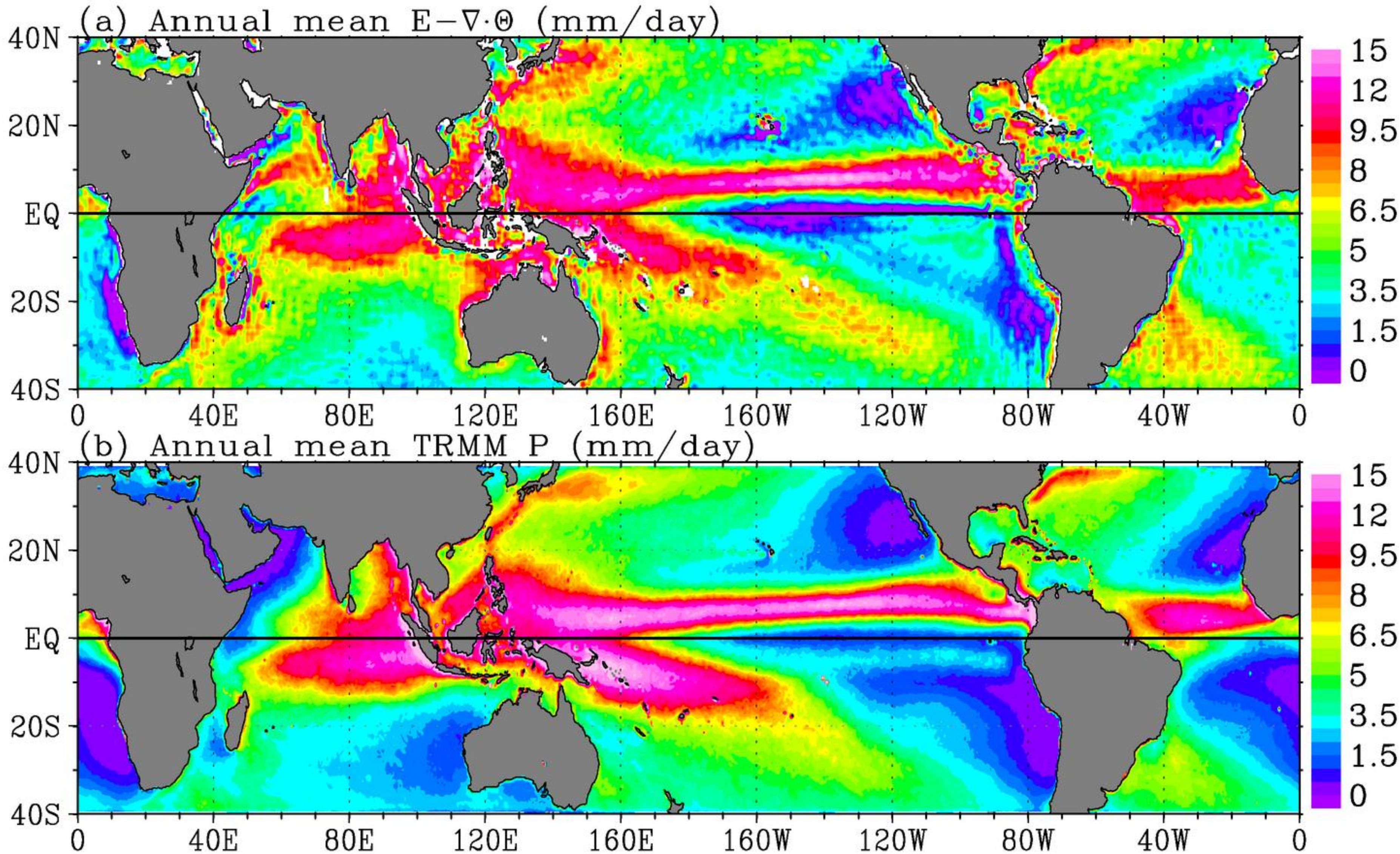
Budyko (1974) 12

River discharge

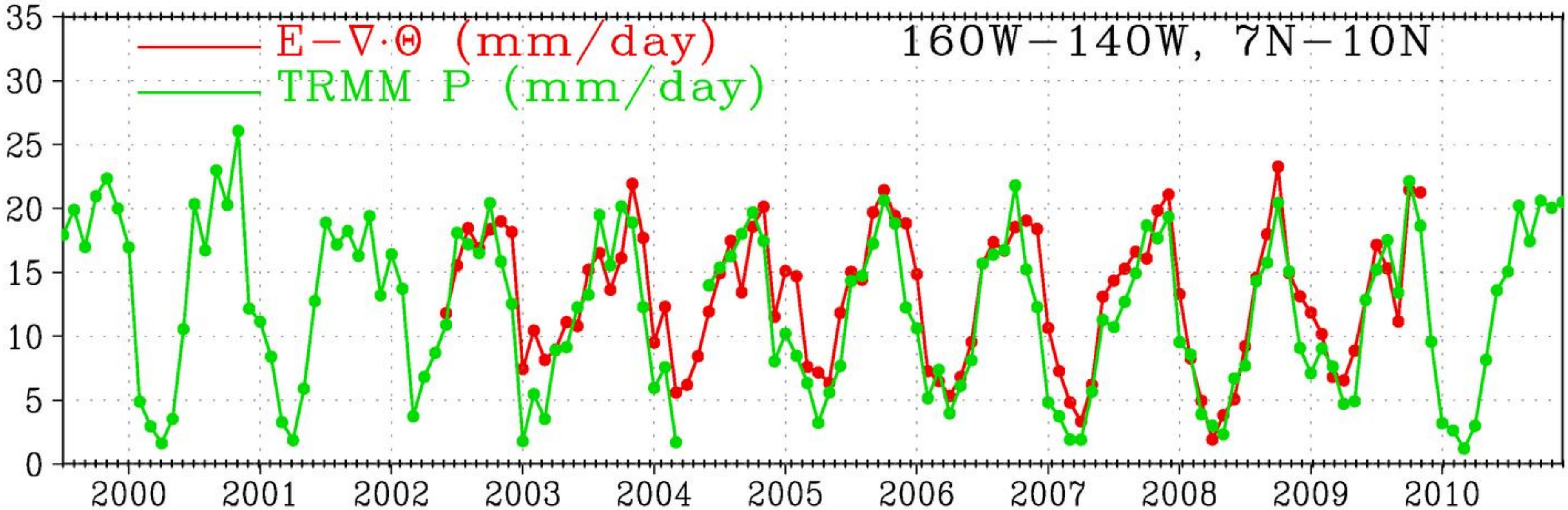
Dai (2002) 8.6

Mean / standard deviation

2.14±2.62 (10^8kg/s)



(a) Annual mean E−∇·Θ (mm/day)
40N
20N
EQ
20S
40S
0
40E
80E
120E
160E
160W
120W
80W
40W
0
15
12
9.5
8
6.5
5
3.5
1.5
0
(b) Annual mean TRMM P (mm/day)
40N
20N
EQ
20S
40S
0
40E
80E
120E
160E
160W
120W
80W
40W
0
15
12
9.5
8
6.5
5
3.5
1.5
0



E−∇·Θ (mm/day)
TRMM P (mm/day)
160W−140W, 7N−10N
35
30
25
20
15
10
5
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010

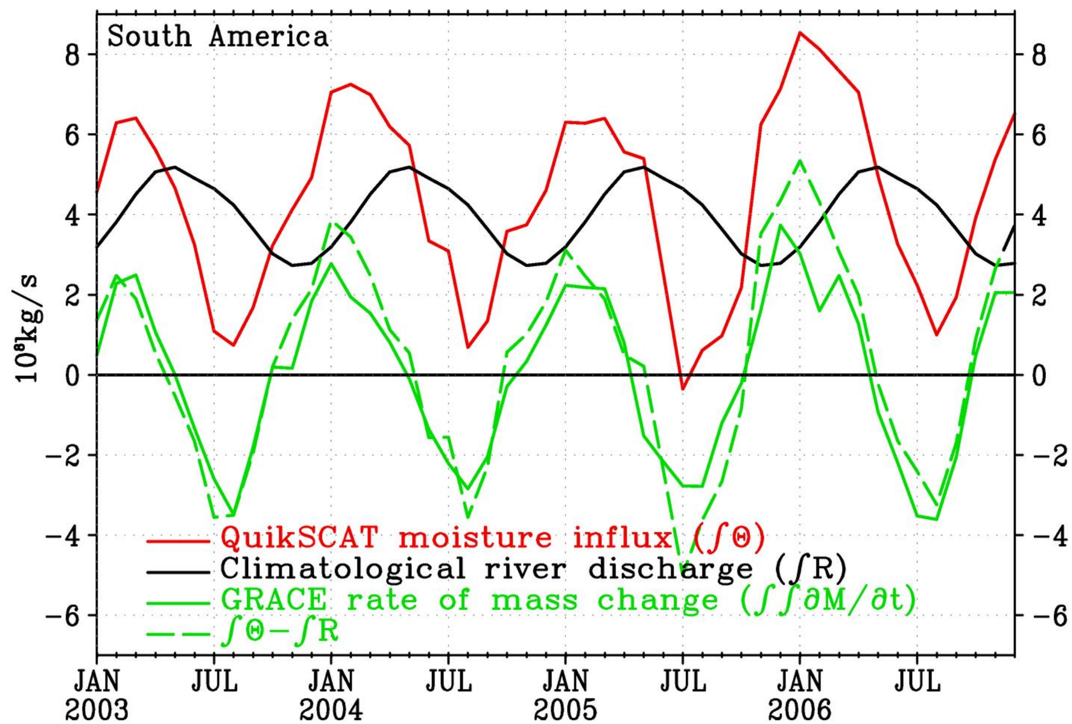
Land Balance

Water Balance over South America

$$\iint \frac{\partial M}{\partial t} = \int \Theta - \int R$$

GRACE Liu/Xie Dai/Trenberth

$$\iint (P-E) = \int \Theta$$



Mean / standard deviation

0.36±0.93 (10^8kg/s)

Four-year means in cm/yr

Moisture into continent

Liu	76.1

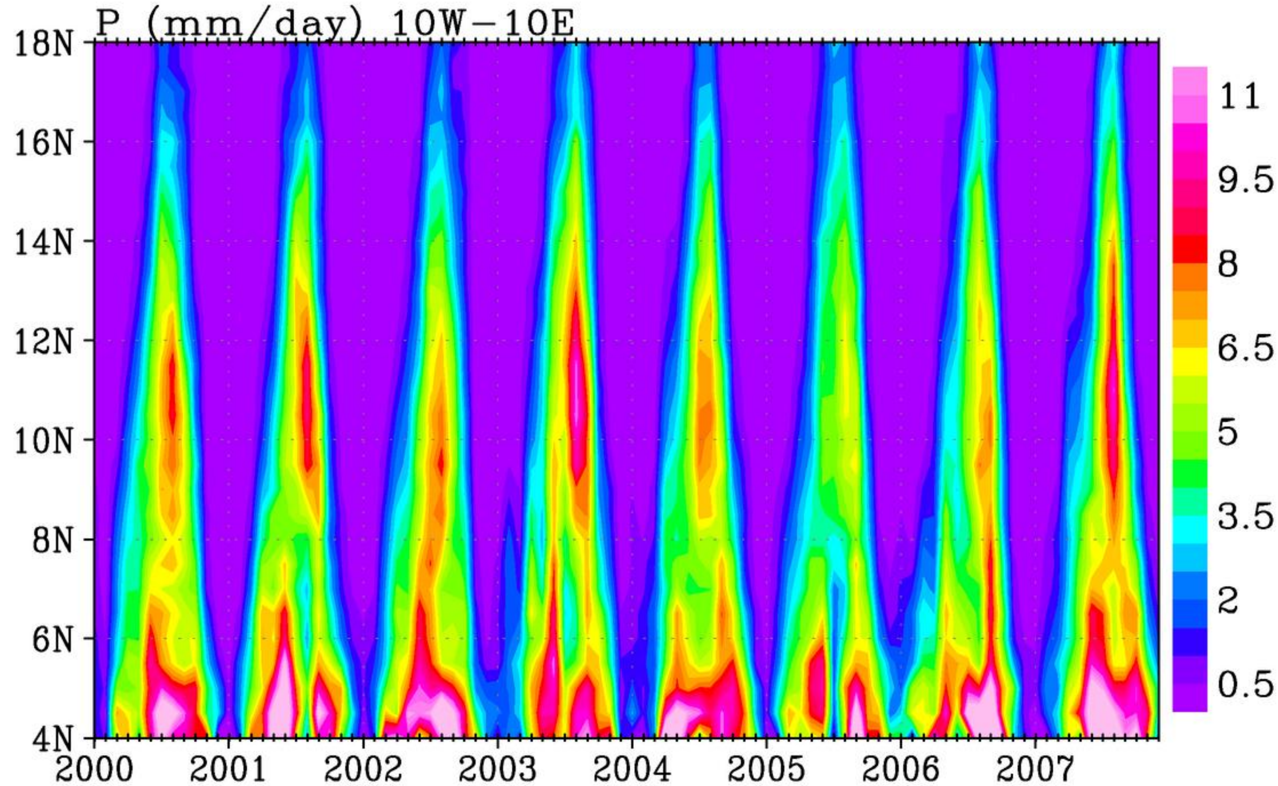
P-E

NEWS	61.3
Budyko (1974)	73

River discharge

Dai (2002)	69.2

Sahel Precipitation Jump

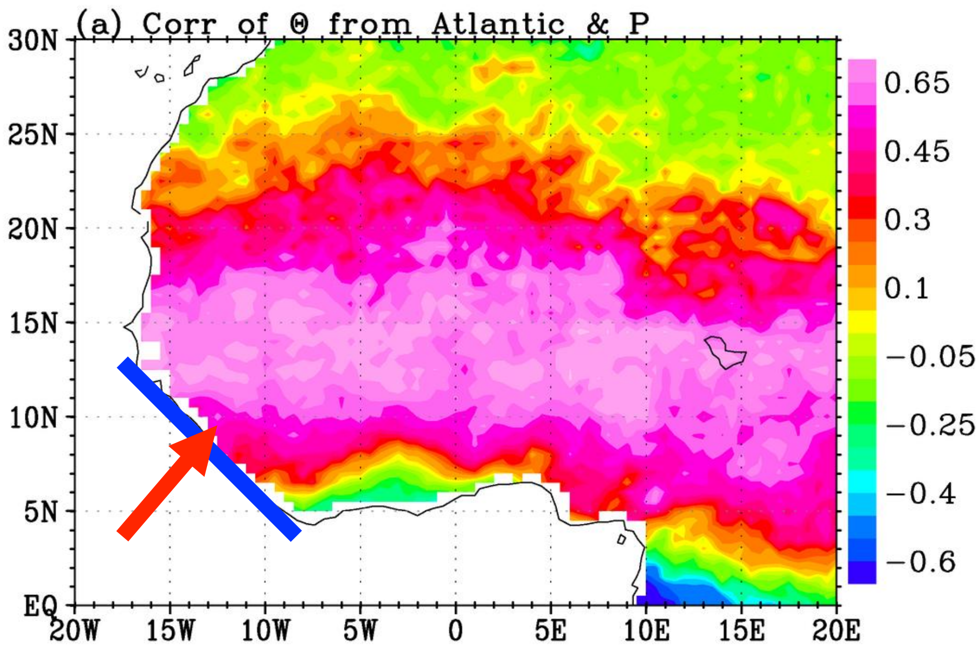


Past hypothesis:

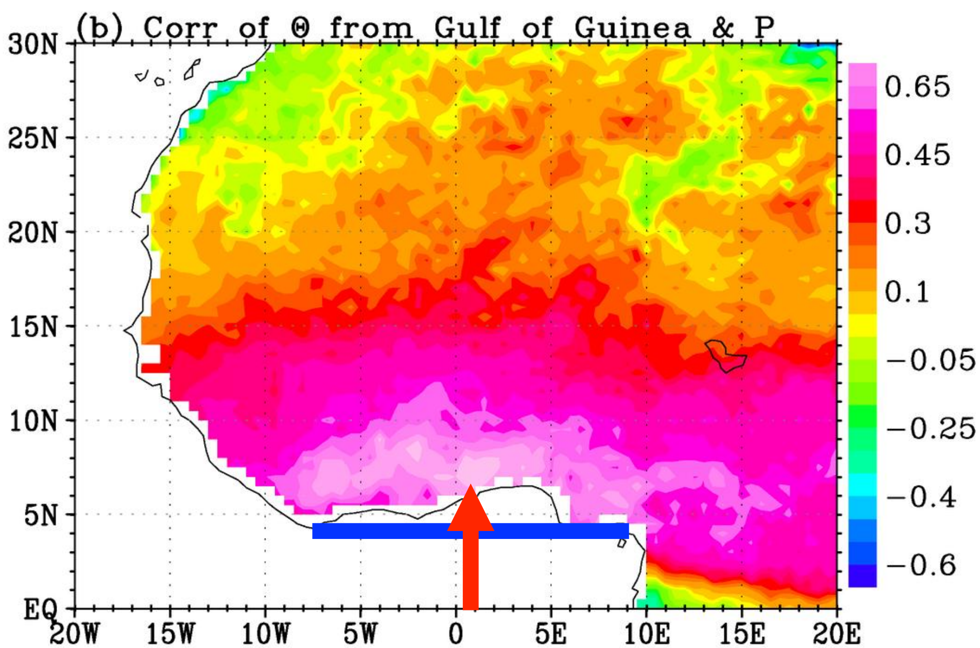
Caused by meridional transport of moisture from Gulf of Guinea following ITCZ-true for southern rainfall

Sahel rainfall – (1) an extension of moisture from Gulf of Guinea, but there is a phase difference; (2) from synoptic instability of easterly waves, but the waves blow over dry continent out to the ocean and do not have August peak.

Oceanic influence from Gulf of Guinea and Atlantic

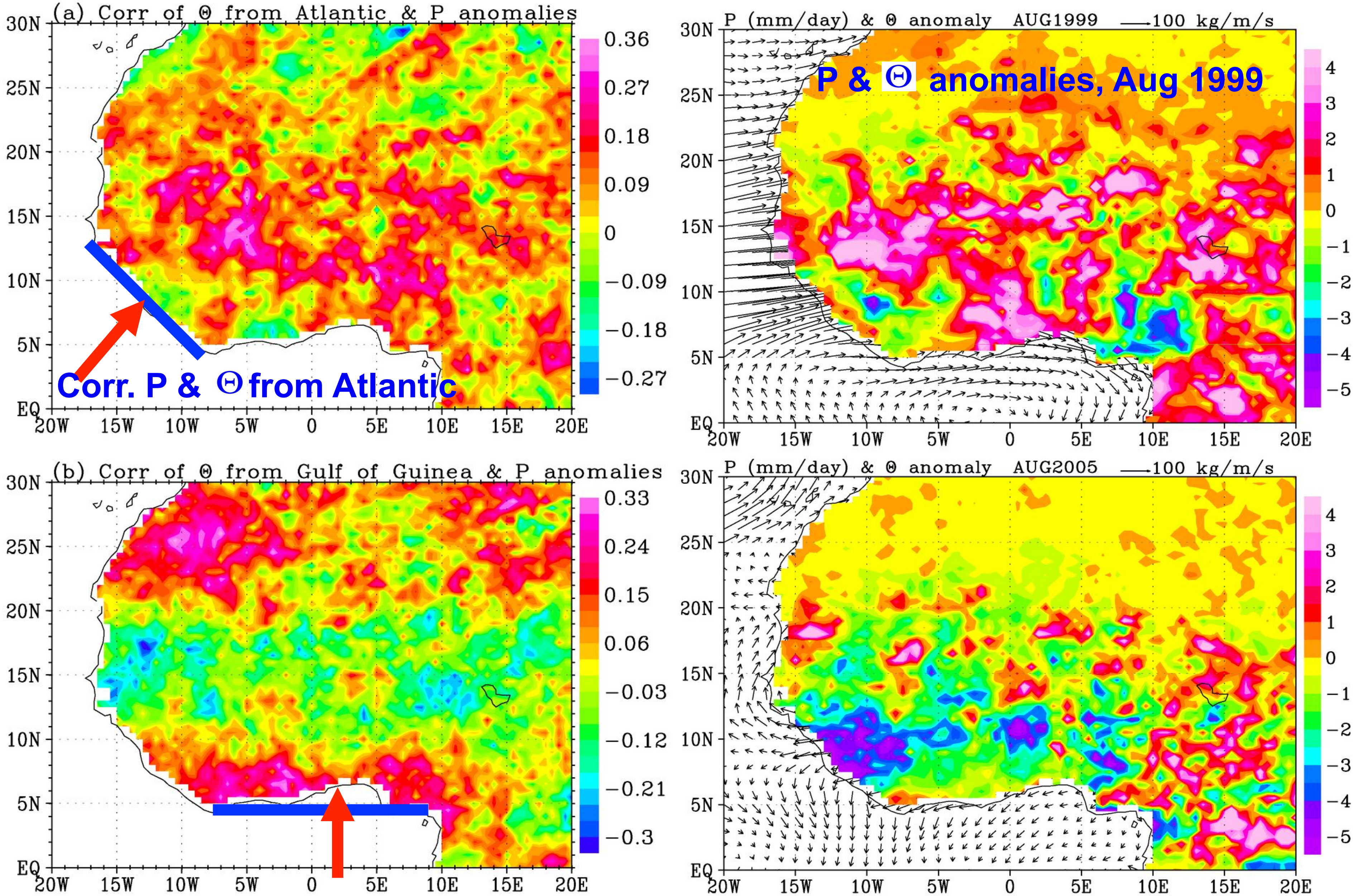


Corr. P & Θ from Atlantic



Corr. P & Θ from Gulf of Guinea

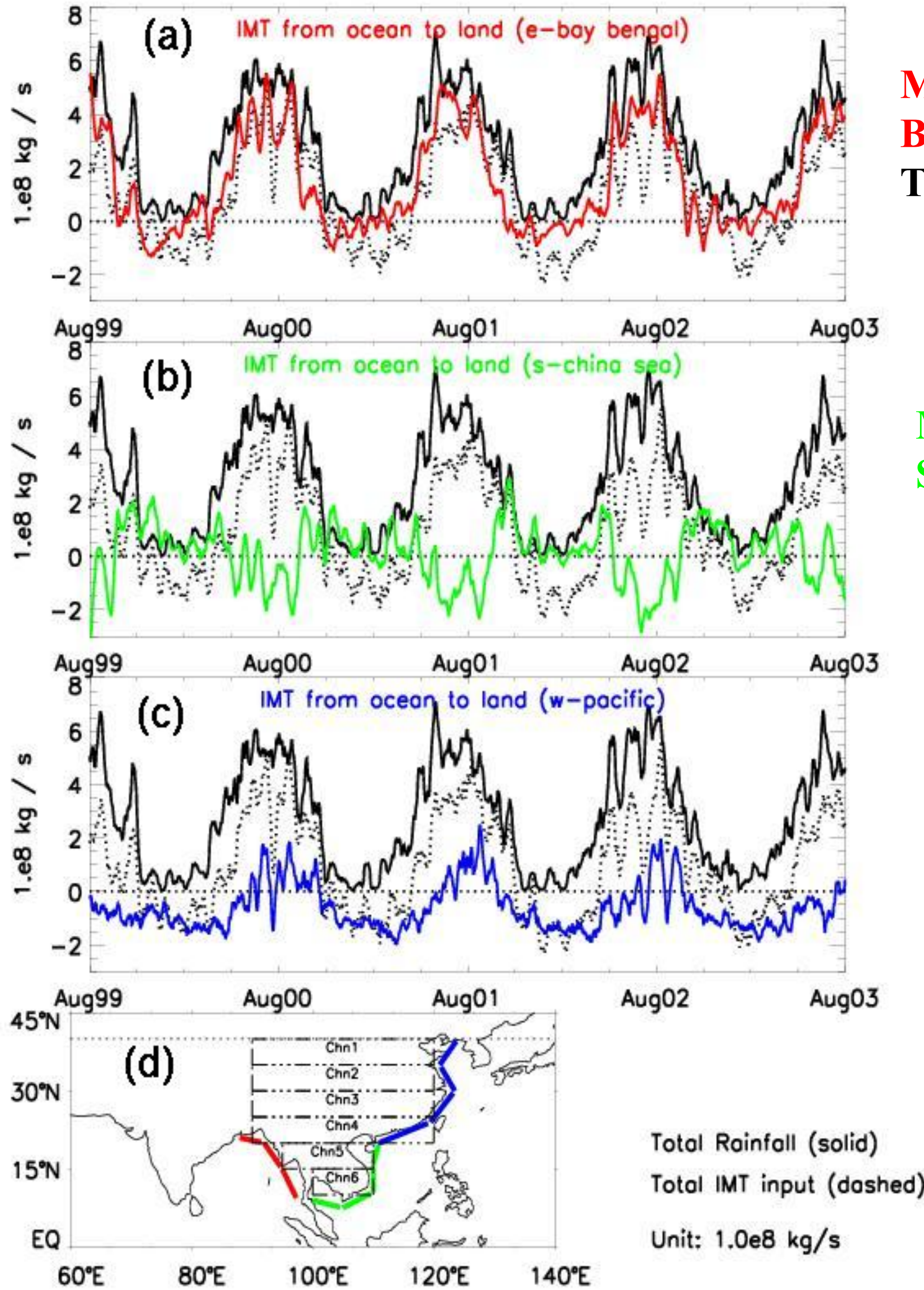
Interannual Anomalies



Corr. P & Θ from Gulf of Guinea

P & Θ anomalies, Aug 2005

East Asian Monsoon



Moisture transport from Bay of Bengal

TRMM precipitation

Moisture transport from Southern Ocean

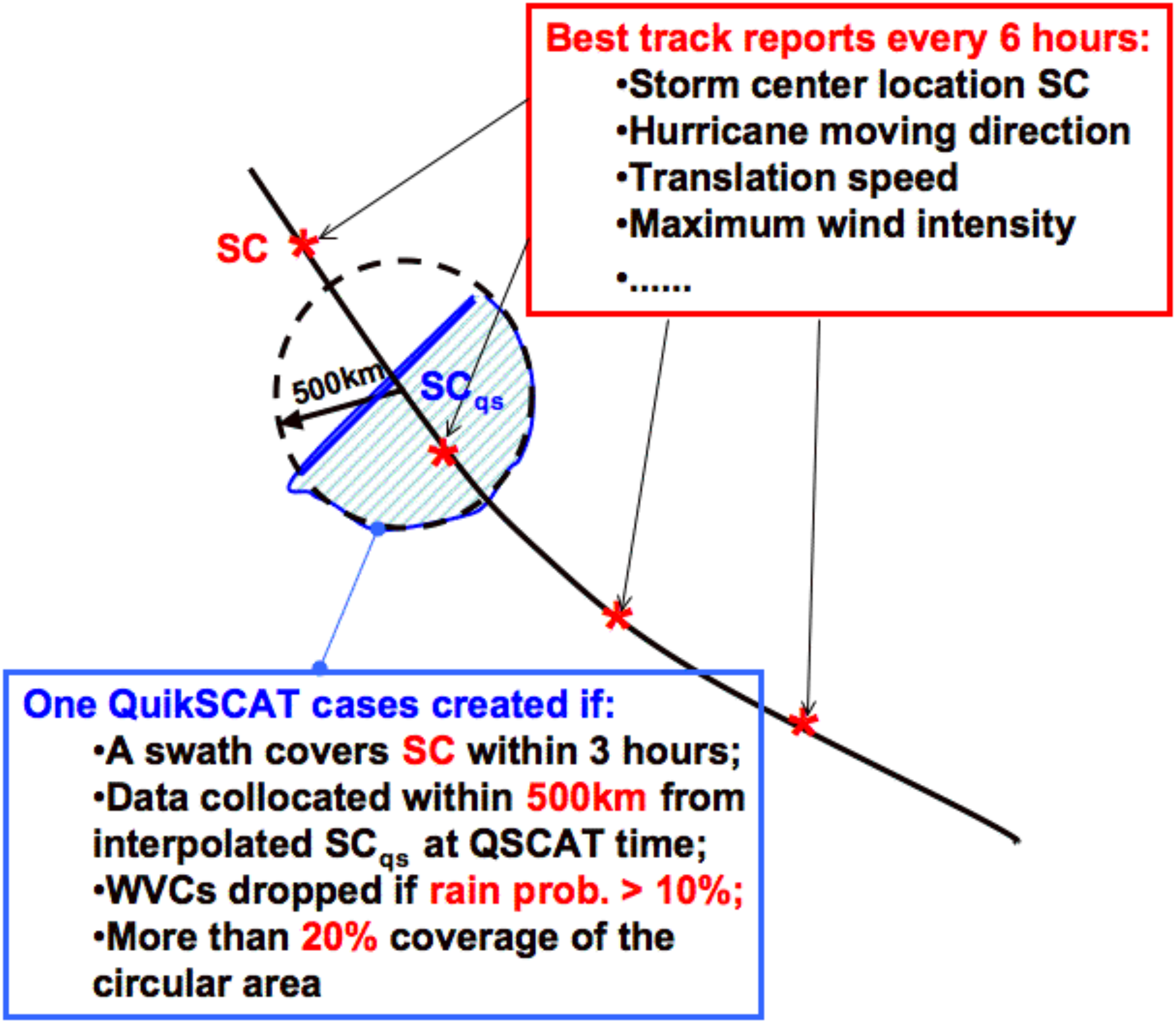
Moisture transport from Pacific

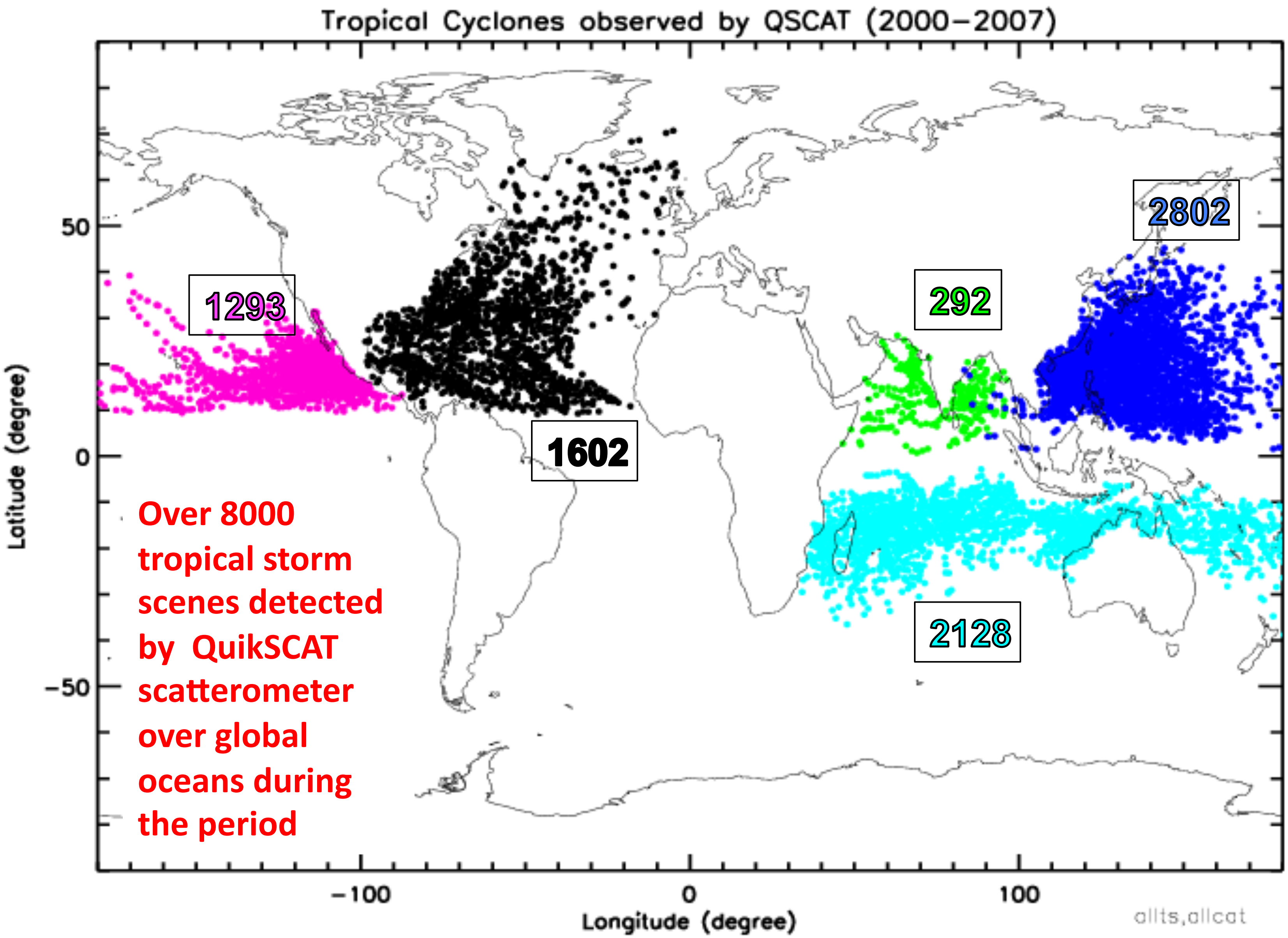
Seasonal rain change is controlled by moisture transport from Bay of Bengal

Balance in Hurricane

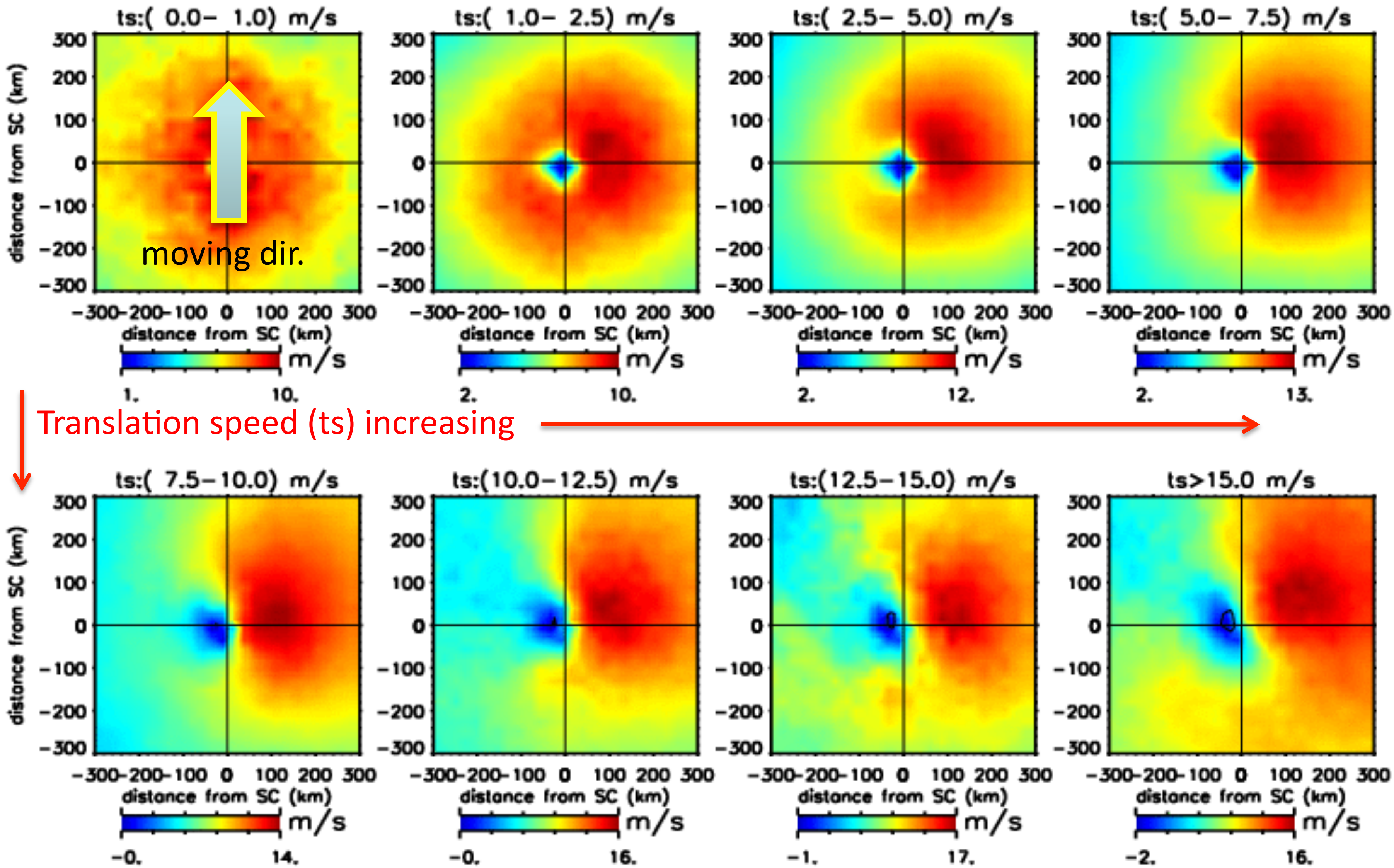
Hurricane composite

- ❖Traditional measurements rarely give a complete map of hurricane structure; mapping usually depends of the extrapolation of measurements along aircraft flight paths or from point measurements of opportunity.
- ❖Wide-swath scatterometer or radiometer are the best mean for synoptic mapping of a hurricane, but the map generated in one pass may still not be complete.
- ❖Characteristics of symmetry with respect to translation direction that are independent of the size of the hurricane are examined through composites of over 8000 scans of QuikSCAT and TMI, collocated to operational best track information, over global oceans in a decade.


Best track reports every 6 hours:
•Storm center location SC
•Hurricane moving direction
•Translation speed
•Maximum wind intensity
•......
SC
500km
SCqs
One QuikSCAT cases created if:
•A swath covers SC within 3 hours;
•Data collocated within 500km from interpolated SCqs at QSCAT time;
•WVCs dropped if rain prob. > 10%;
•More than 20% coverage of the circular area

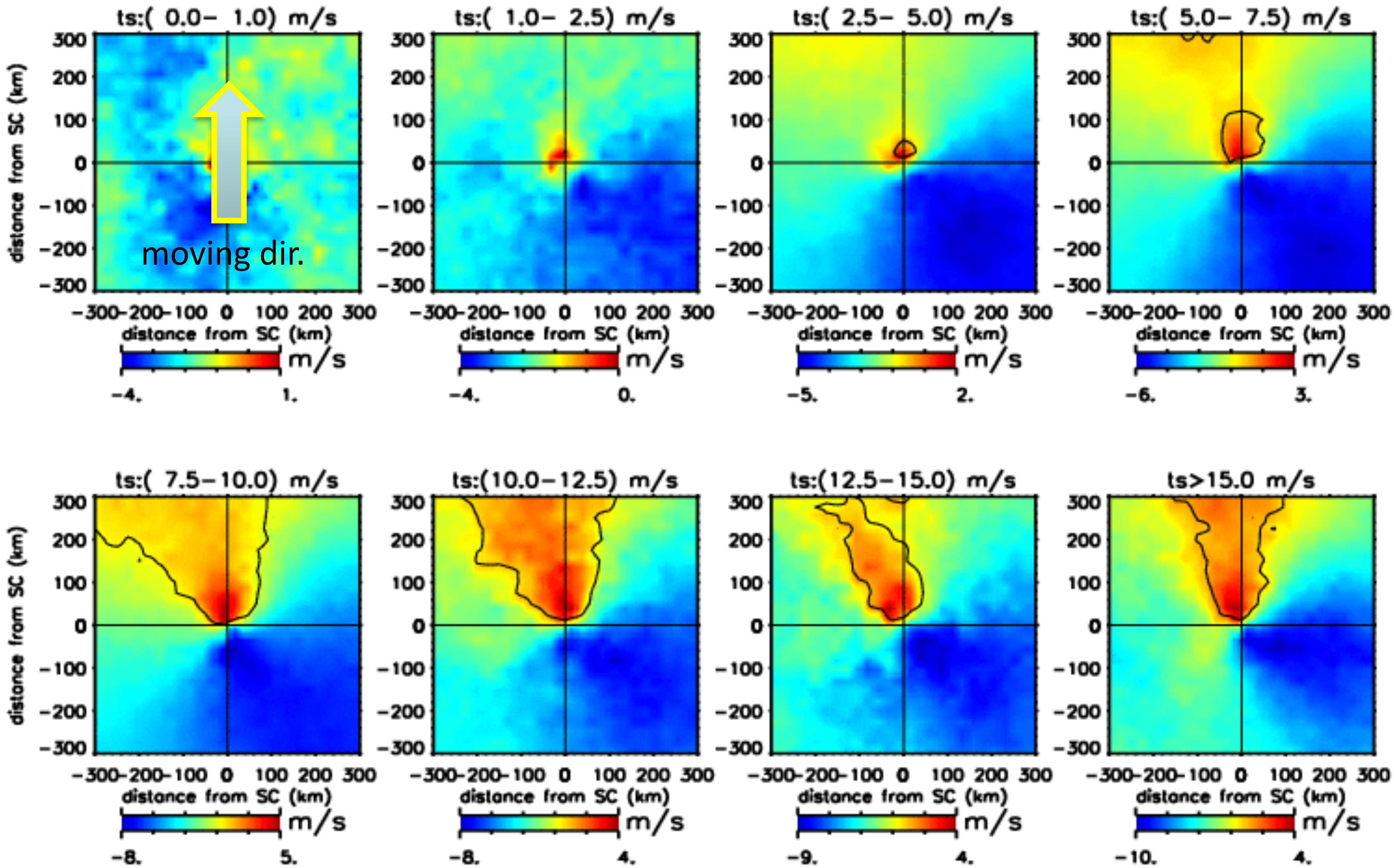

Tropical Cyclones observed by QSCAT (2000−2007)
Latitude (degree)
Longitude (degree)
50
0
−50
−100
0
100
1293
1602
292
2802
2128
Over 8000 tropical storm scenes detected by QuikSCAT scatterometer over global oceans during the period
allts,allcat

Composite of Tangential (v) Wind in N. Hemis. 2000-2007



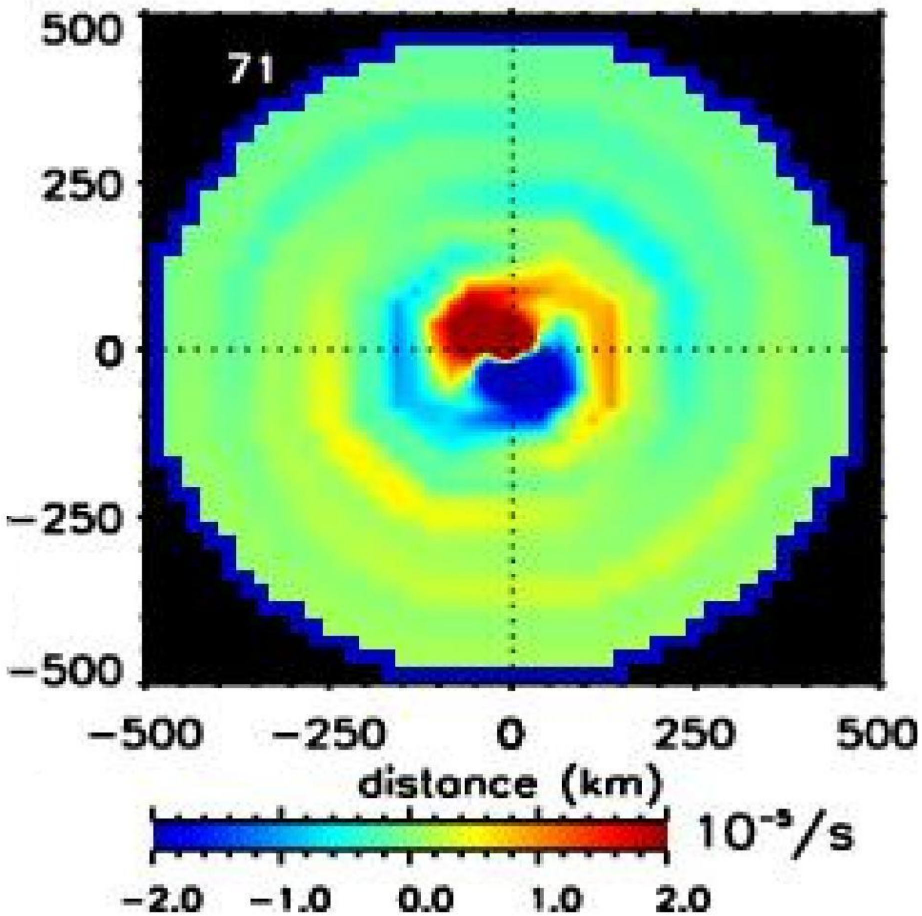
The tangential component is near symmetric for slow-moving storms. The left-right asymmetry induced by and becomes stronger for fast-moving storms.

Composite of Radial (u) Wind in N. Hemisphere 2000-2007



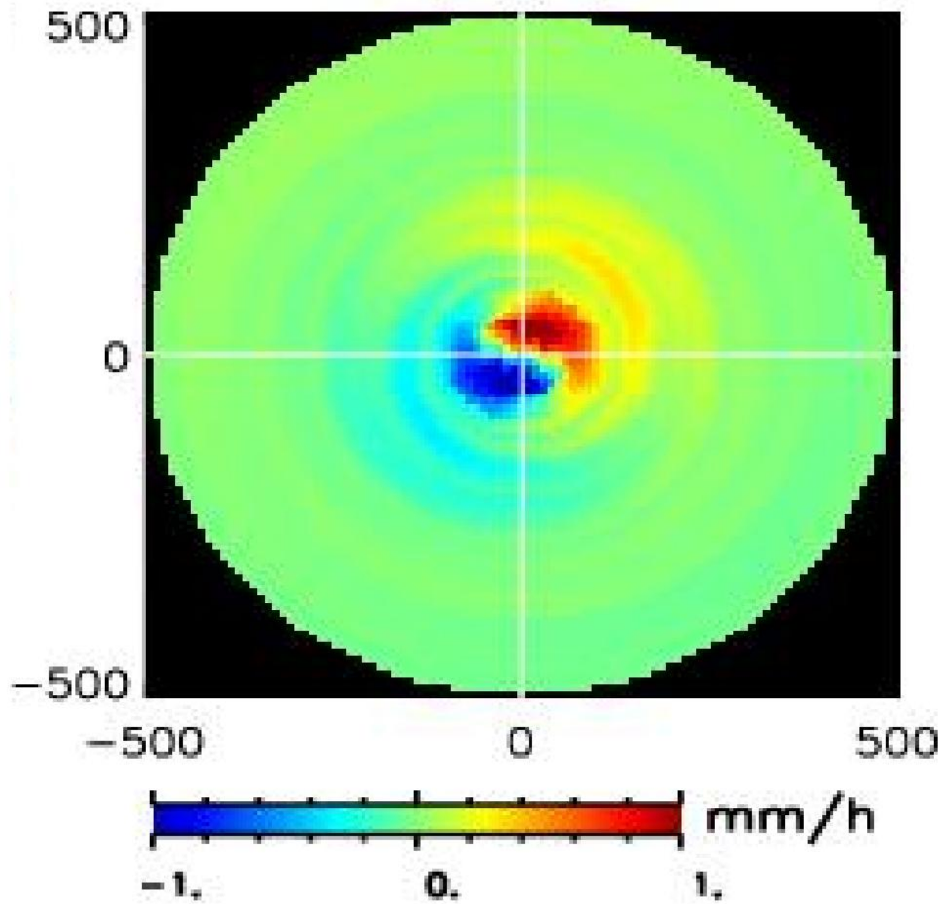
Radial wind component indicates inflow around storm center with maximum from right-rear; also detects area of outflow in front when translation speed picks up

Tropical Cyclone Asymmetry



First mode M1

QuikSCAT wind convergence
2000-2007
Translation speed >3 m/s

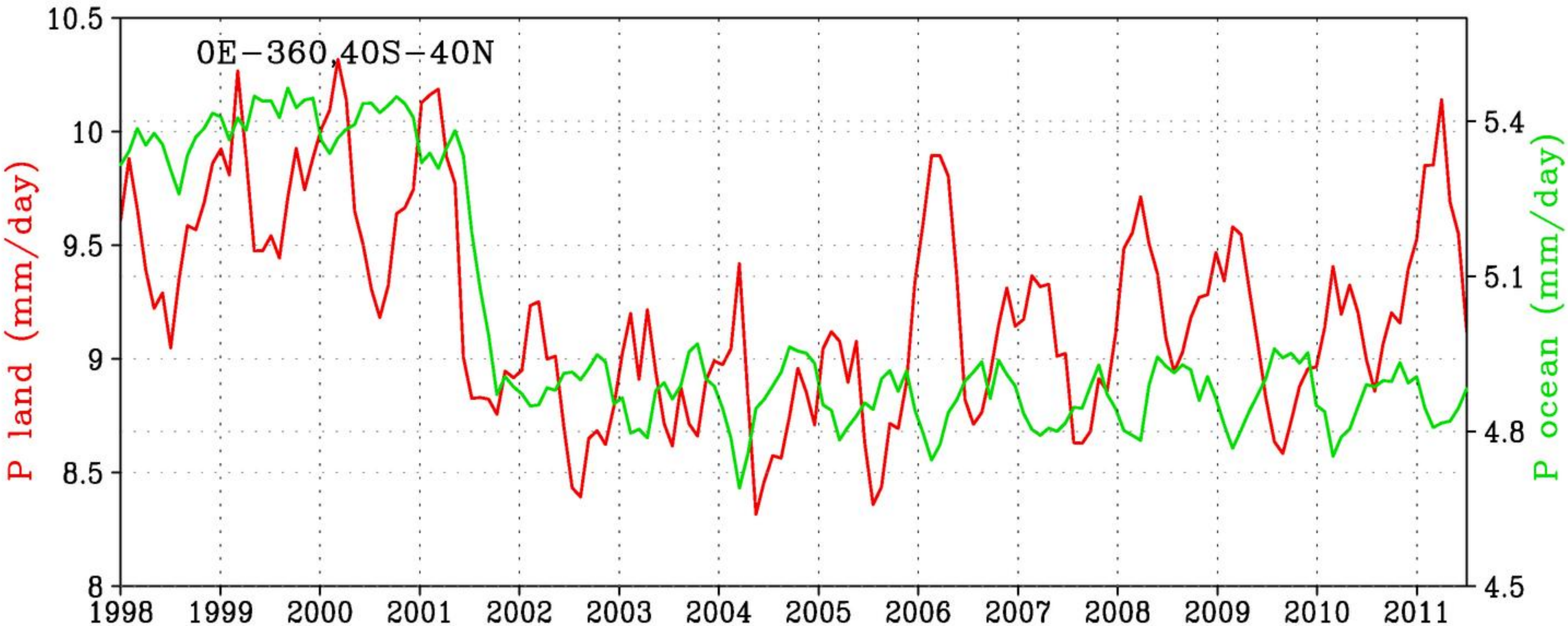


First mode M1

TRMM 2A12 rainfall
2002-2007
Translation speed >7 m/s

Anomaly patterns of precipitation and surface wind convergence have a phase shift.

Moisture convergence at surface may be followed by strong upward motion in the eye wall, and may return as precipitation in the later phase of the cyclonic circulation.



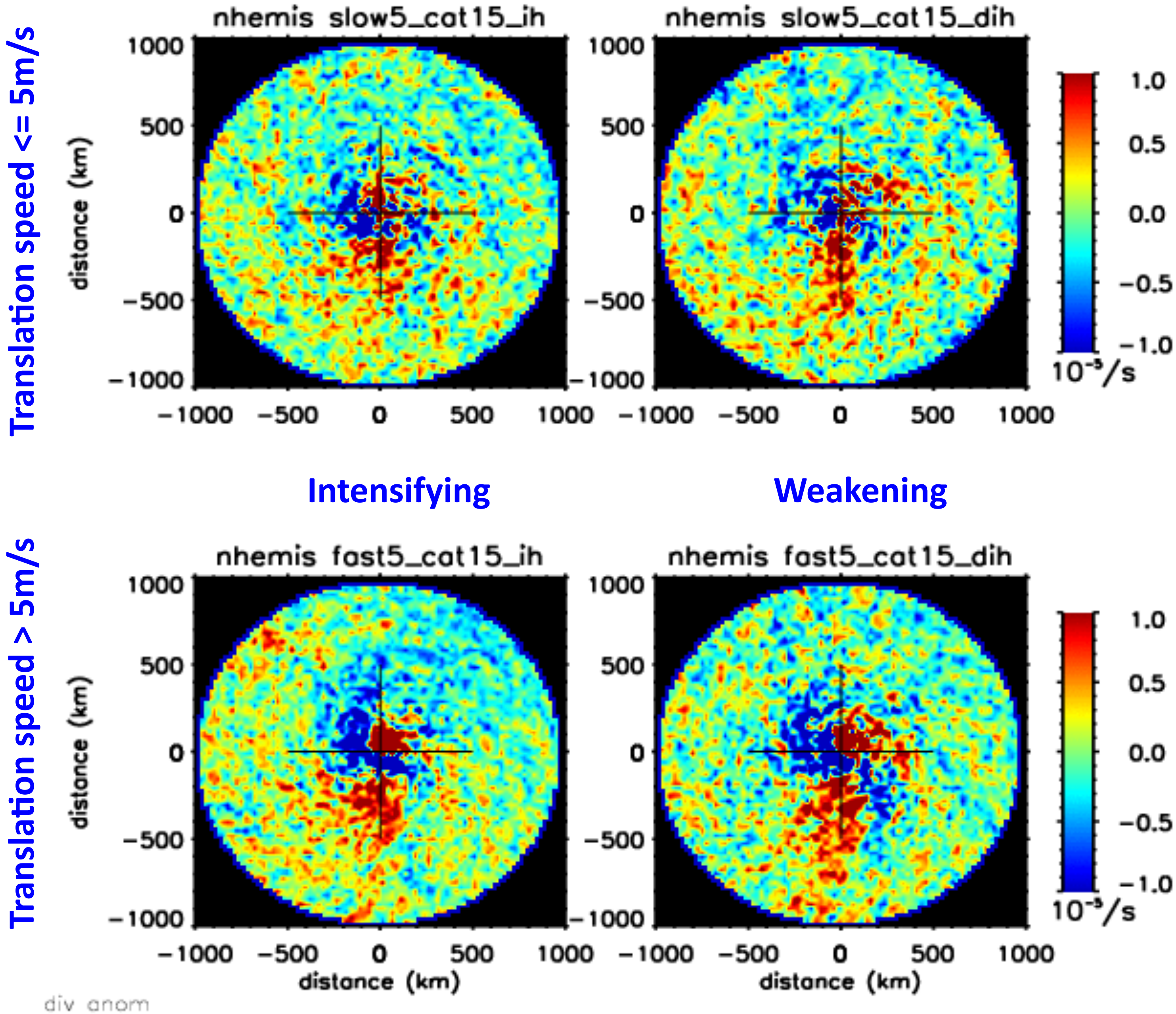
0E-360,40S-40N
P land (mm/day)
P ocean (mm/day)
10.5
10
9.5
9
8.5
8
5.4
5.1
4.8
4.5
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011

Backup

- **The results infer that the strong asymmetry induced by fast-moving storms may act like a built-in break, hindering cyclone intensification.**

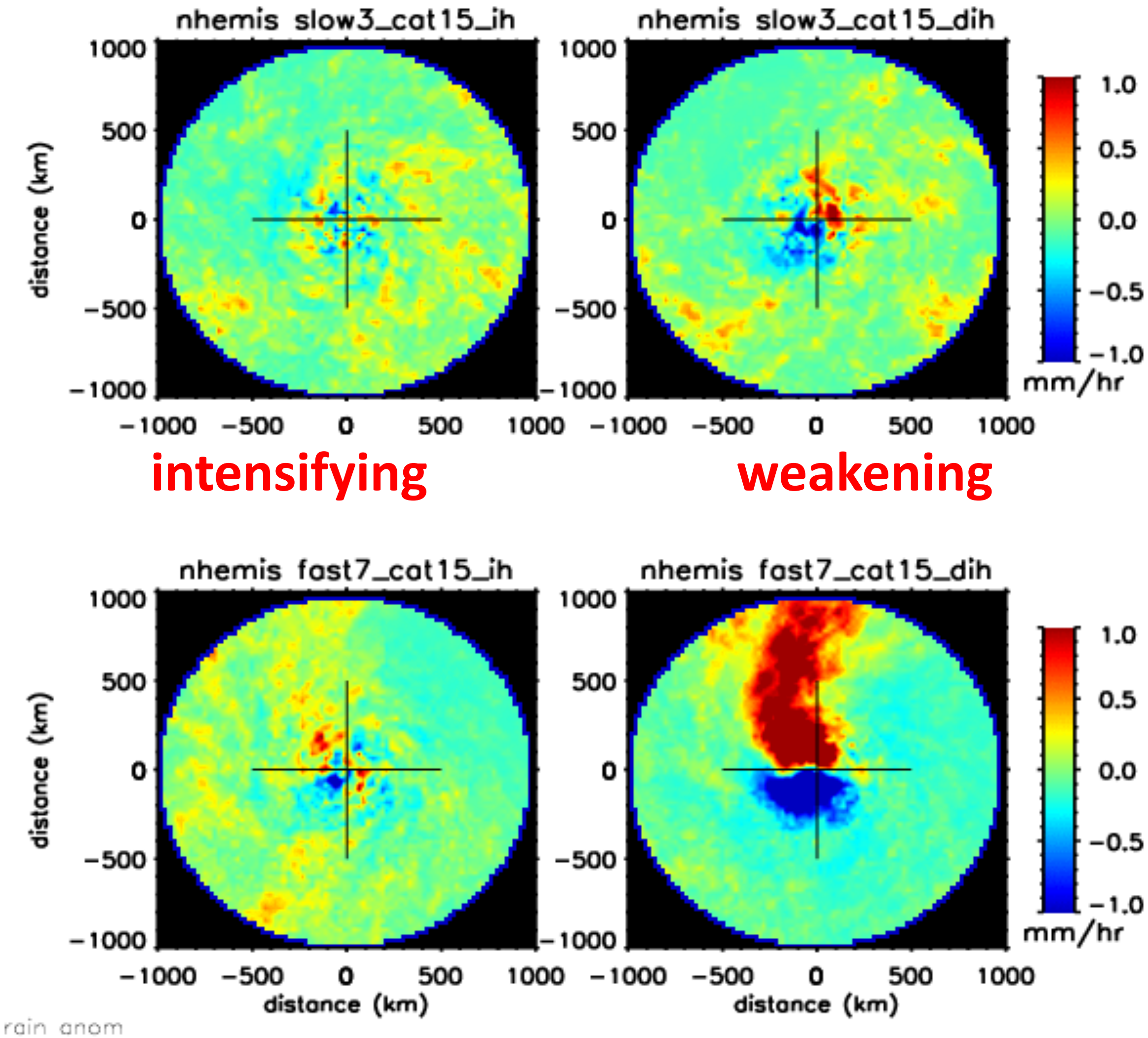
- **We are trying to relate wind convergence to other satellite measurements:**
  - **precipitation (TRMM/TMI)**
  - **SST (AMSR)**
  - **Rain profile (TRMM/PR)**

Northern Hemisphere, 2000-2007, all tropical storms, Convergence (anomaly)



Anomaly : composite with annular mean removed

Composite of Surafce Rainrate (Annular Anomaly) in N. Hemis. 2000-2007

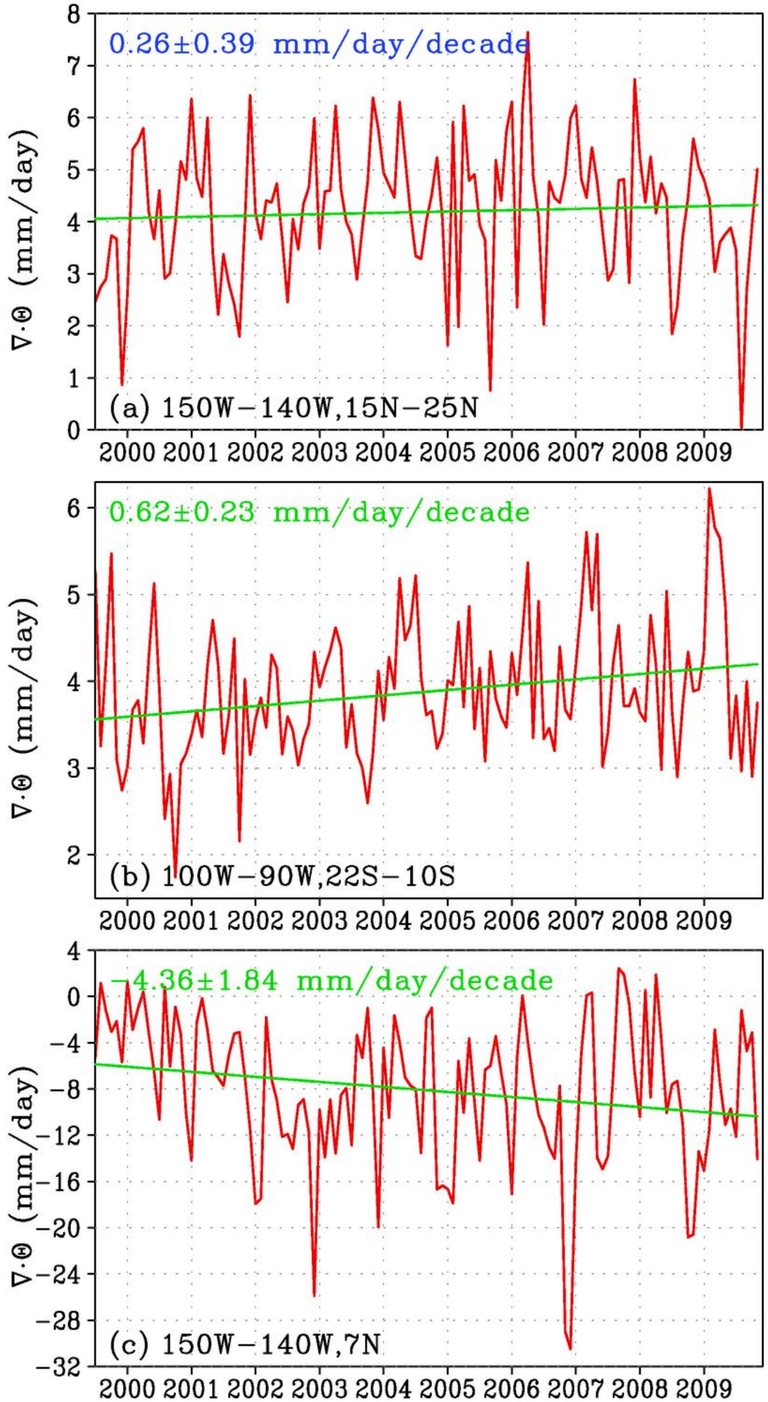


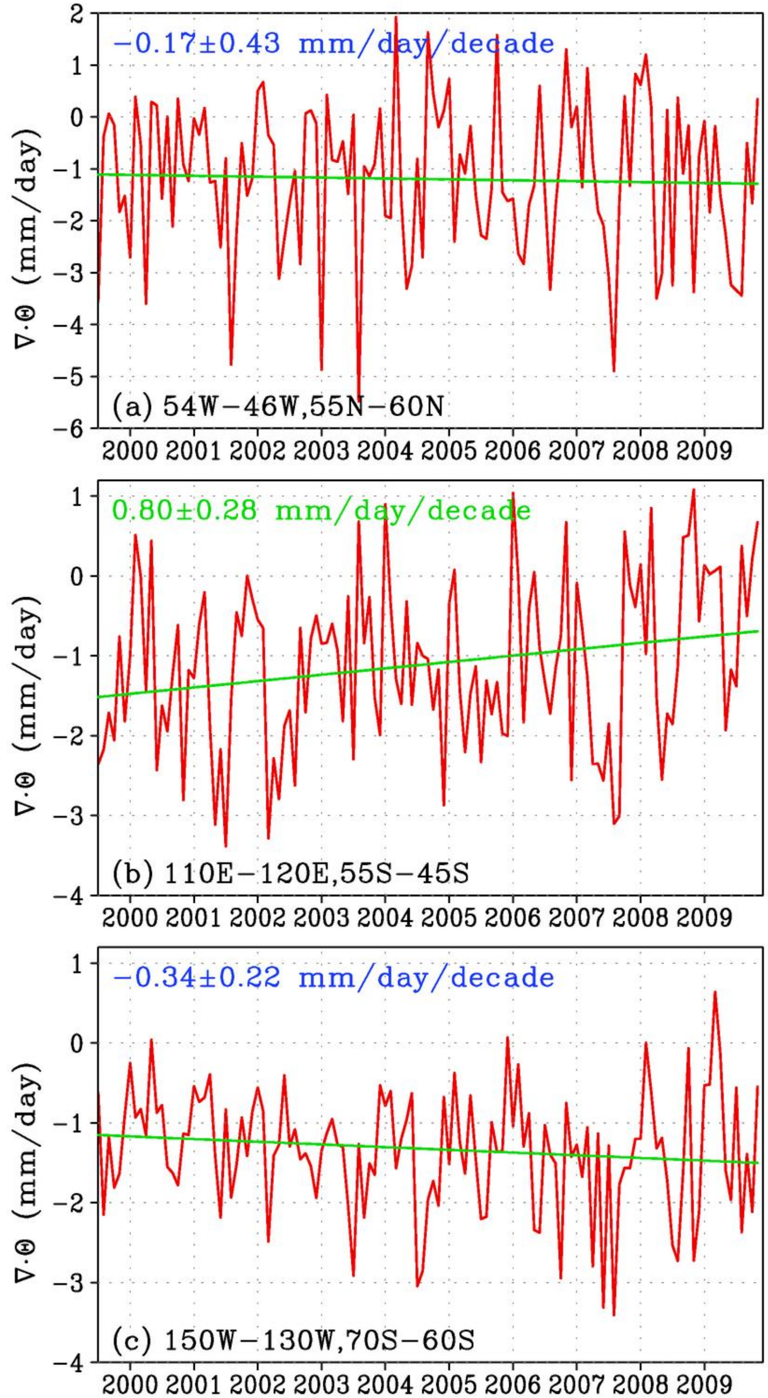
Slow moving (TS < 3m/s)

All cases in hurricane category (V_{max} > 64 knots)

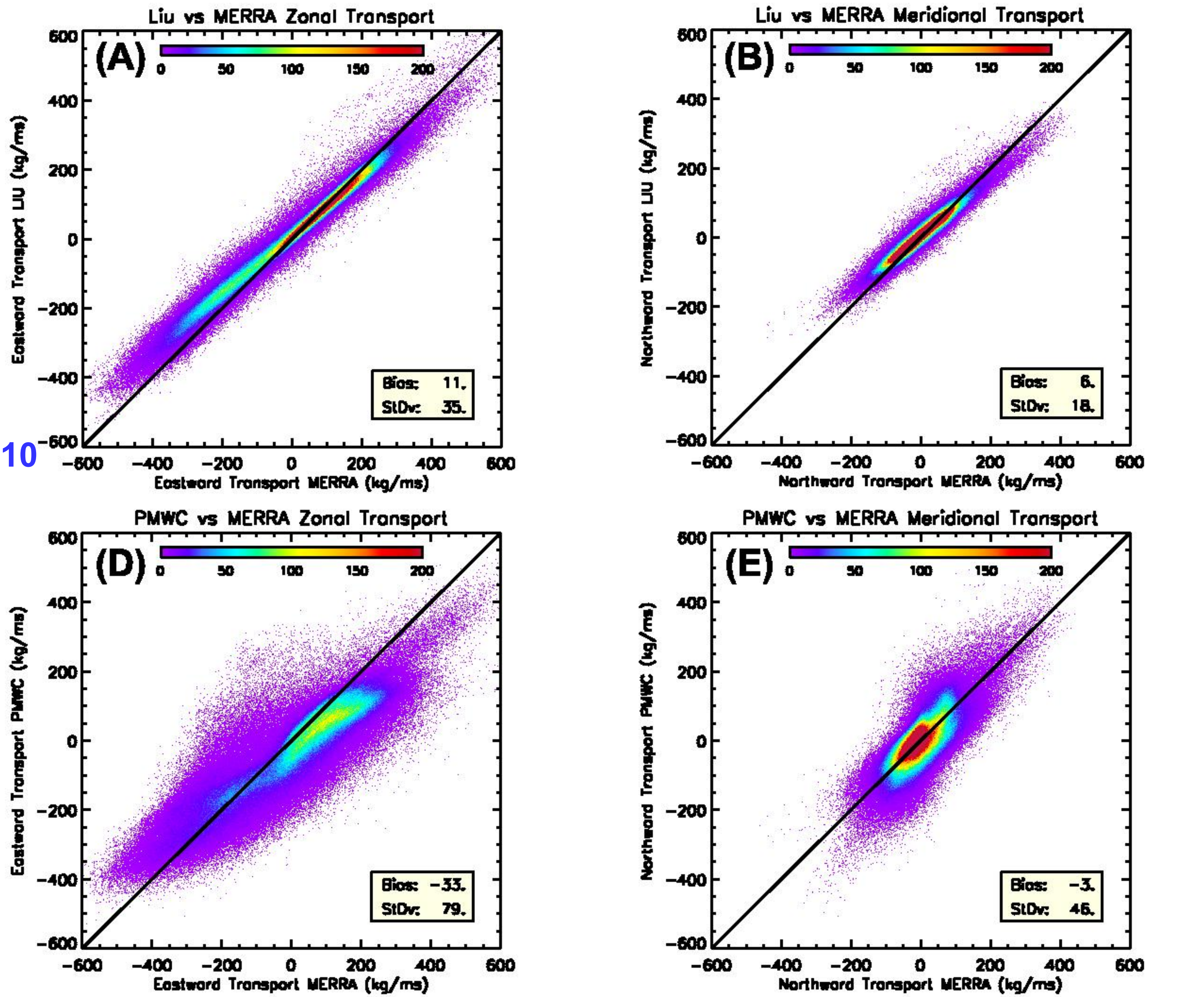
Fast moving (TS > 7 m/s)

The strongest rain rate anomaly is observed in the front-left quadrant, associated with weakening fast-moving storms.

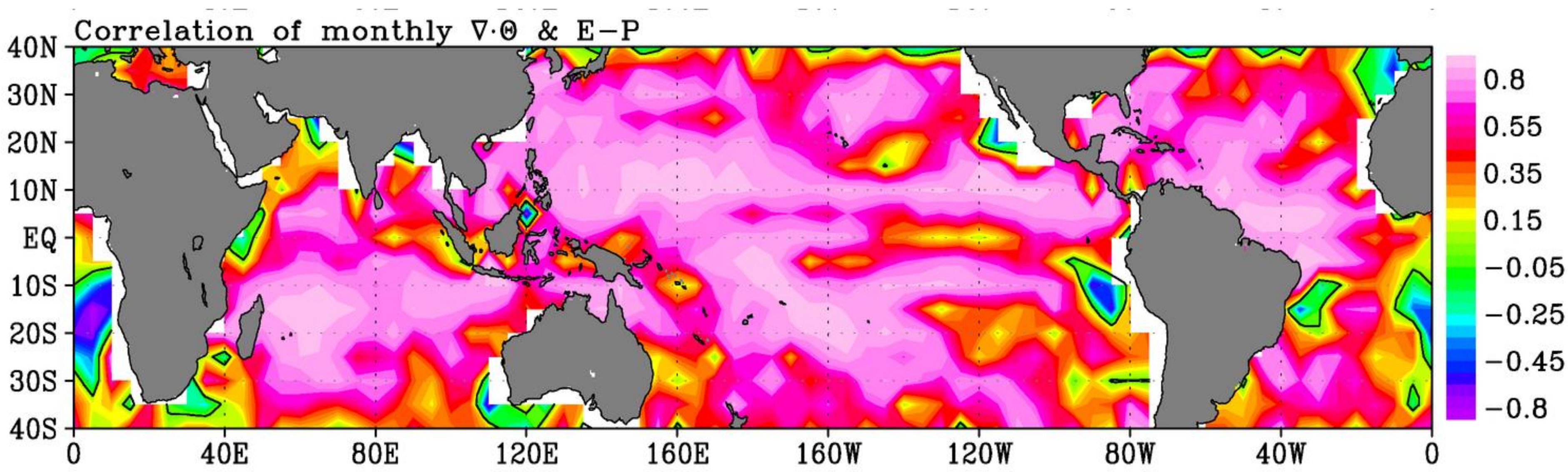

0.26±0.39 mm/day/decade
(a) 150W−140W,15N−25N
∇·Θ (mm/day)
0.62±0.23 mm/day/decade
(b) 100W−90W,22S−10S
∇·Θ (mm/day)
−4.36±1.84 mm/day/decade
(c) 150W−140W,7N
∇·Θ (mm/day)
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

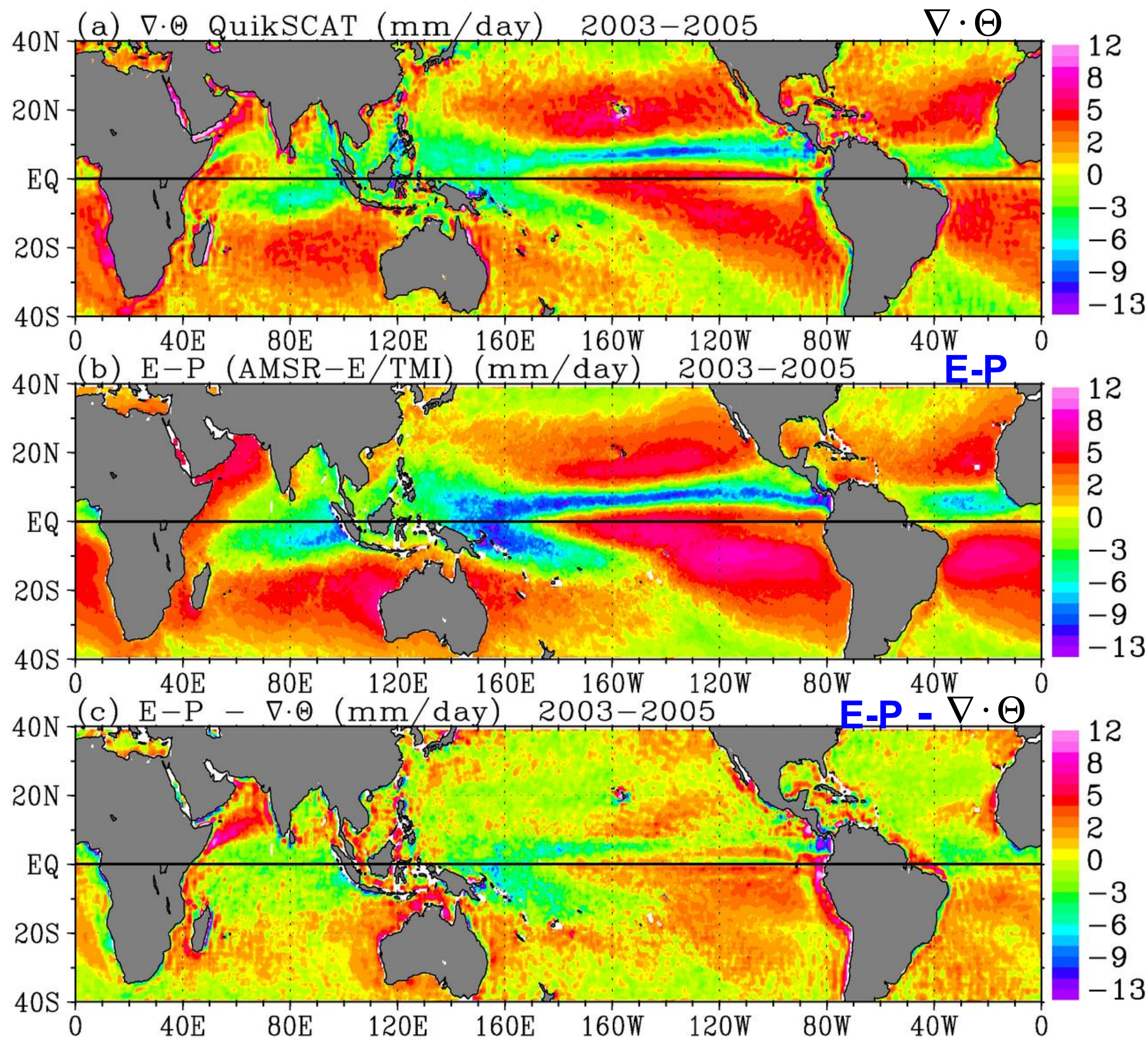

−0.17±0.43 mm/day/decade
(a) 54W−46W,55N−60N
0.80±0.28 mm/day/decade
(b) 110E−120E,55S−45S
−0.34±0.22 mm/day/decade
(c) 150W−130W,70S−60S
∇·Θ (mm/day)
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

Hilburn 2010
2000-2008
Monthly
N=950203



Correlation of $\nabla \cdot \Theta$ and E-P




(a) ∇·Θ QuikSCAT (mm/day) 2003−2005
∇·Θ
(b) E−P (AMSR−E/TMI) (mm/day) 2003−2005
E-P
(c) E−P − ∇·Θ (mm/day) 2003−2005
E-P - ∇·Θ
40N
20N
EQ
20S
40S
0
40E
80E
120E
160E
160W
120W
80W
40W
12
8
5
2
0
−3
−6
−9
−13

Amplification of the water cycle Induced by Global Warming

- Wet regions would get wetter and dry regions get drier.
- Hypothesis was built on numerical model results
- Observational support from very limited cruise salinity data
- No credible observation of long-term trends of surface water flux

Ocean Surface Salinity Balance

$$E - P = \frac{h_0}{S_0}\left(\frac{\partial S}{\partial t} + V \cdot \nabla S\right)$$

Spacebased Evaporation

Supply-Side

$$E = C\rho U(q_s - q)$$

A Get q from W

GSFC (GSSTF)
JAPAN (J-OFURO)
German (HOAPS)
Woodshole (OAFLUX)

B Get q from brightness temp.

C Get E from brightness temp.

Demand-Side

$$E = \frac{\partial W}{\partial t} + \nabla \bullet \Theta + P$$

Get Θ from W, Us and U850

Several precipitation products

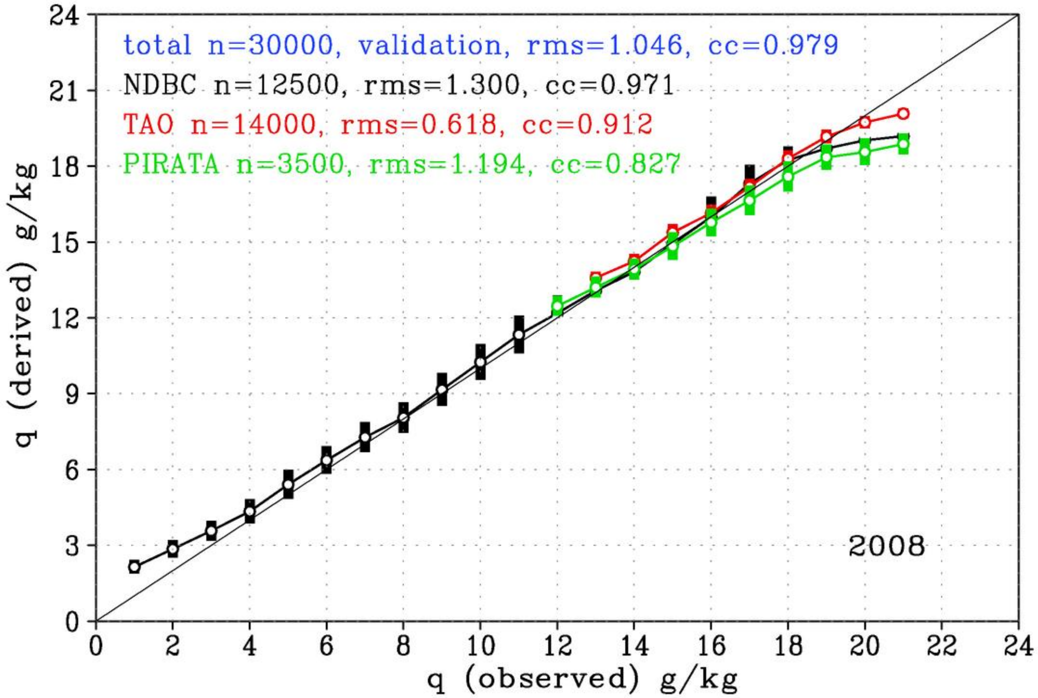
Importance of Water Cycle

(Water is continuously removed from the ocean as excess evaporation over precipitation into the atmosphere redistributed through atmospheric circulation, deposited as excess precipitation over evaporation on land and ice, and returned to the ocean as river discharge and ice-melt)

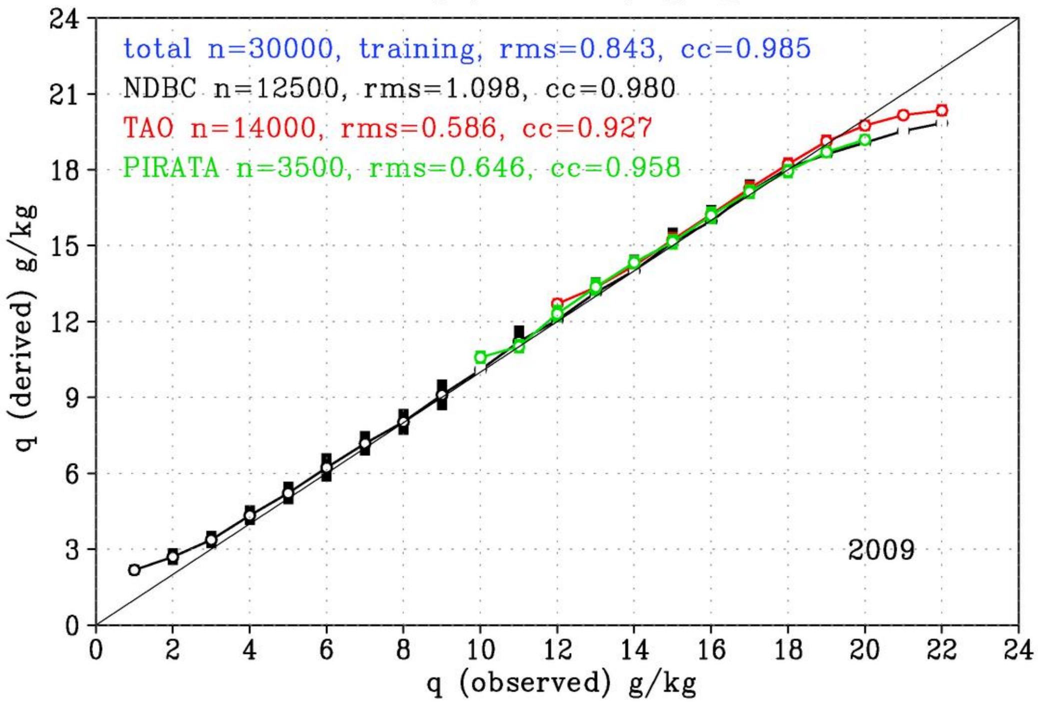
- Critical to existence of human life
- Essential to weather and climate
- Tightly coupled with energy cycle
- High heat capacity and latent heat for storage
- Form clouds and affect radiative balance

Two ways of improving latent heat flux

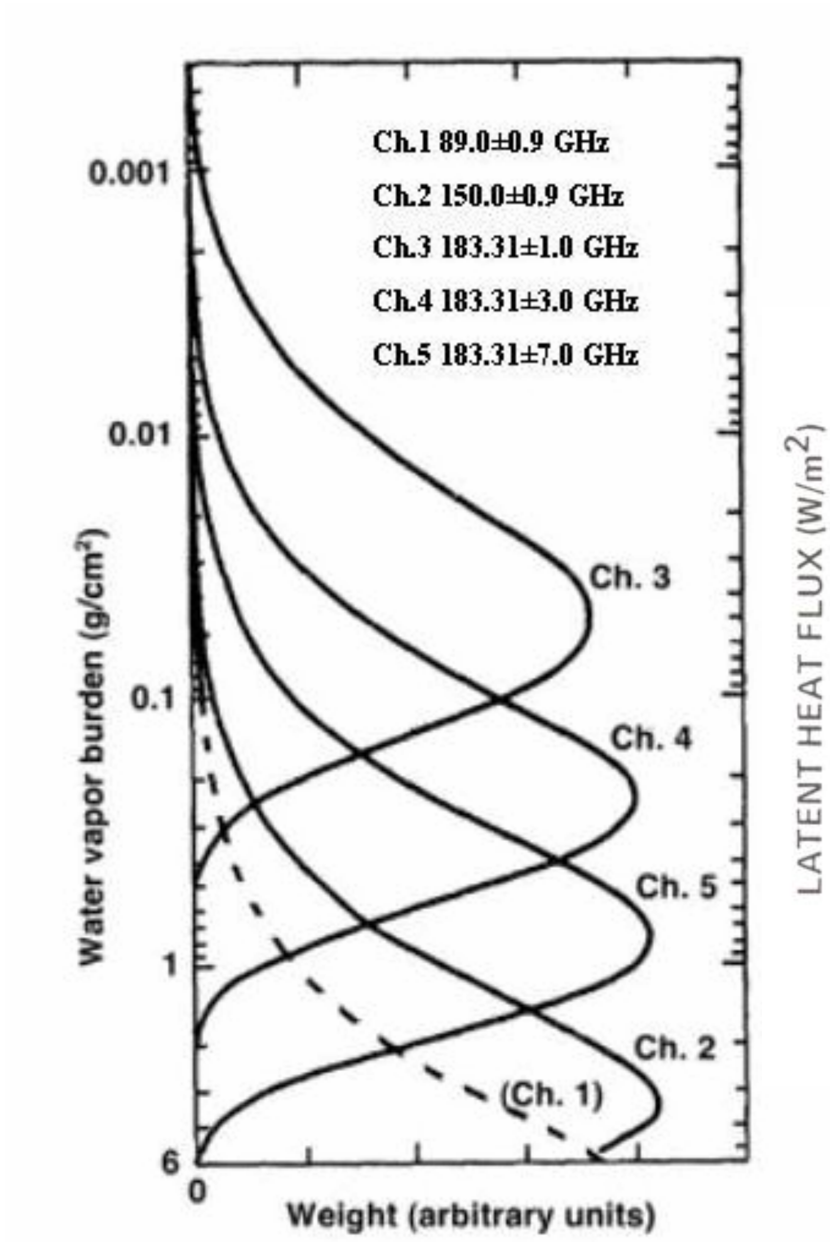
- One way to improve is to add information on the vertical structure of humidity distribution. Liu et al. [1991] shows that in order to account for a larger fraction of variance, at increasing frequencies, larger numbers of independent modes, representing finer vertical structure, are needed. The brightness temperature (BT), measured at the water vapor channels of the Advanced Microwave Sounding Unit (AMSU), could be used
- Liu [1990] also proposed and demonstrated another method of improvement – retrieving E directly from the measured radiances. Such method may improve accuracy in two ways. The first is to by-pass the uncertainties related to the bulk parameterization techniques. The second is to mitigate the magnification of error caused by multiplying inaccurate measurement of wind speed with inaccurate measurements of humidity in the bulk formula.



q validation
N=30,000
NDBC 12500
TAO 14000
PIRATA 3500
rms=1.046 g/kg
CC=0.979

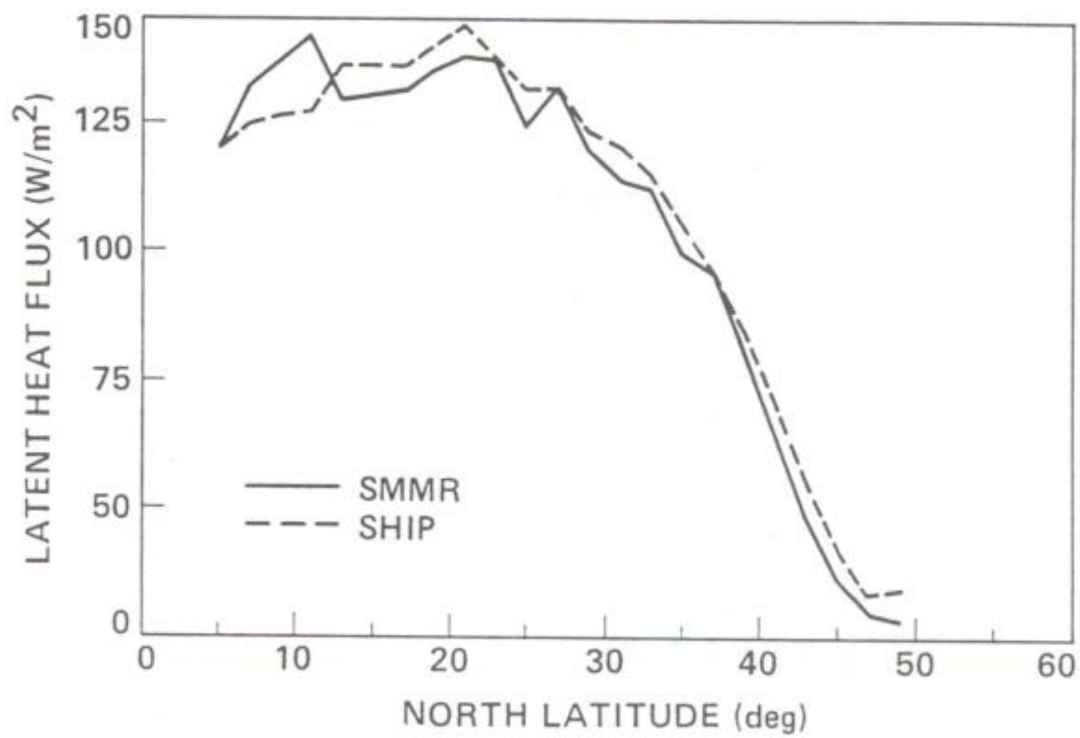


q training
N=30,000
NDBC 12500
TAO 14000
PIRATA 3500
rms=0.843 g/kg
CC=0.985

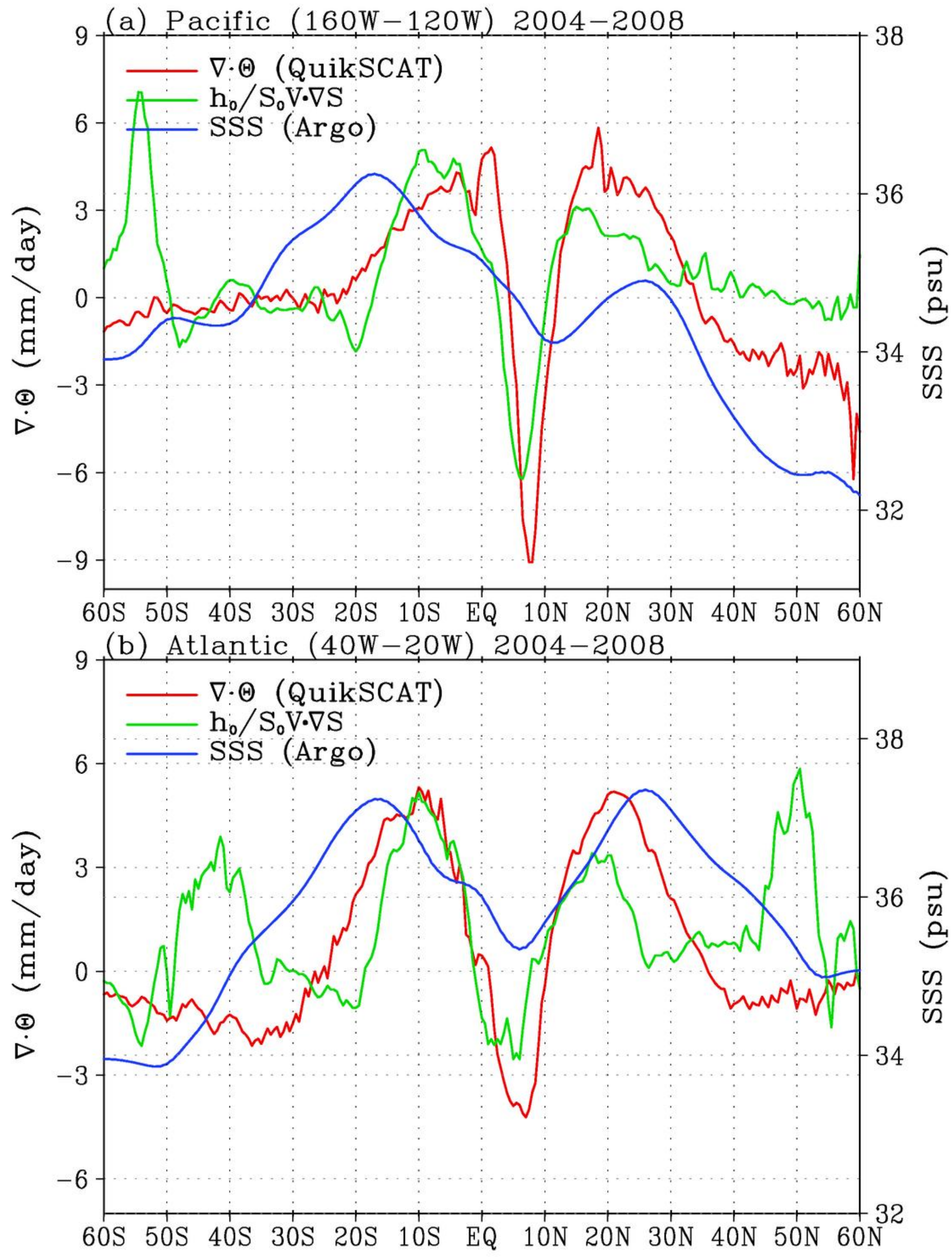


AMSU-B weighting function

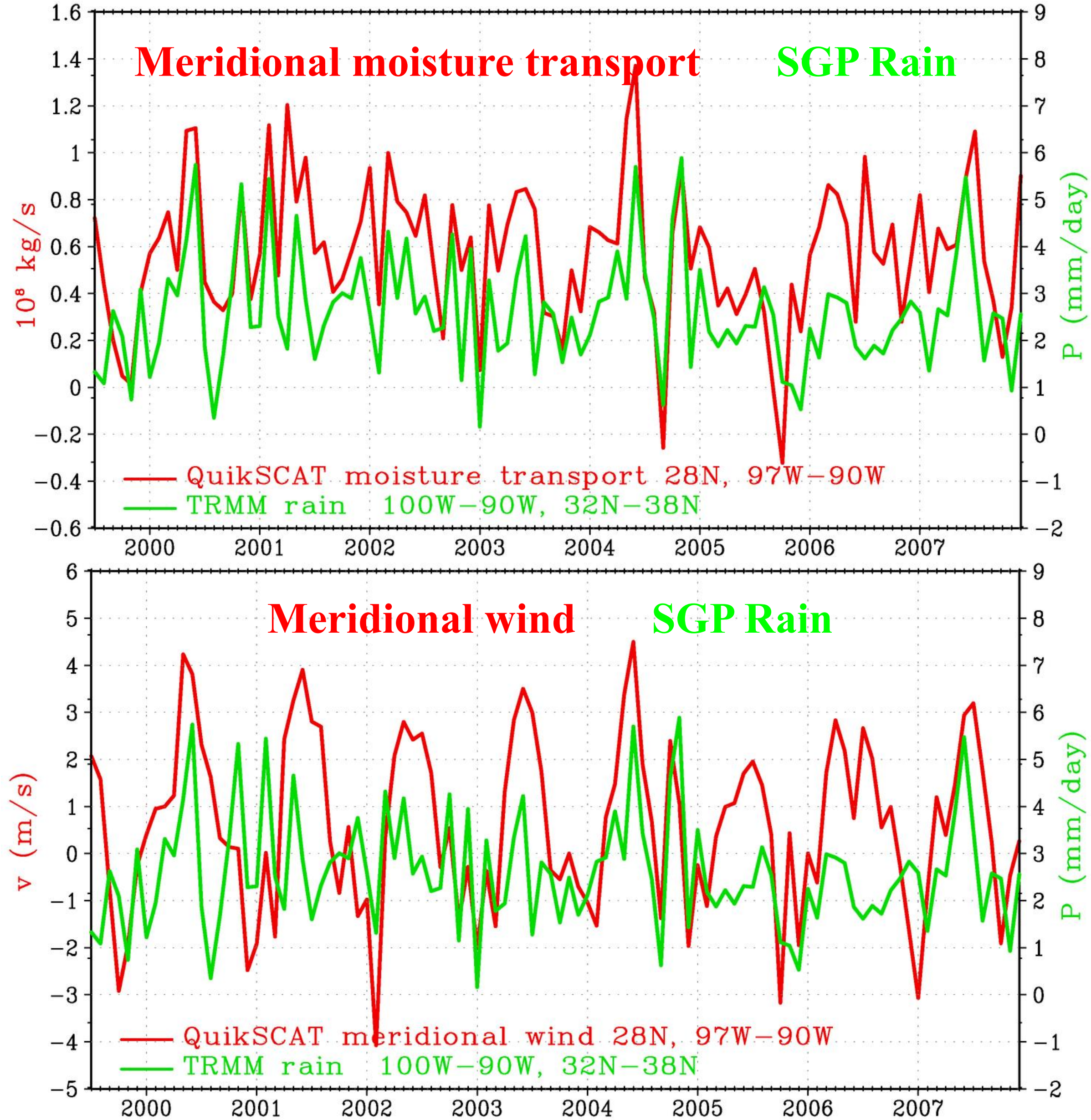
Two ways of improving latent heat flux demonstrated by Liu (1990)



Direct retrieval of LH from SMMR T_B


(a) Pacific (160W−120W) 2004−2008
∇·Θ (QuikSCAT)
h0/S0V·∇S
SSS (Argo)
∇·Θ (mm/day)
SSS (psu)
9
6
3
0
−3
−6
−9
38
36
34
32
60S 50S 40S 30S 20S 10S EQ 10N 20N 30N 40N 50N 60N
(b) Atlantic (40W−20W) 2004−2008
∇·Θ (QuikSCAT)
h0/S0V·∇S
SSS (Argo)
∇·Θ (mm/day)
SSS (psu)
9
6
3
0
−3
−6
38
36
34
32
60S 50S 40S 30S 20S 10S EQ 10N 20N 30N 40N 50N 60N

Southern Great Plains Rain Extremes

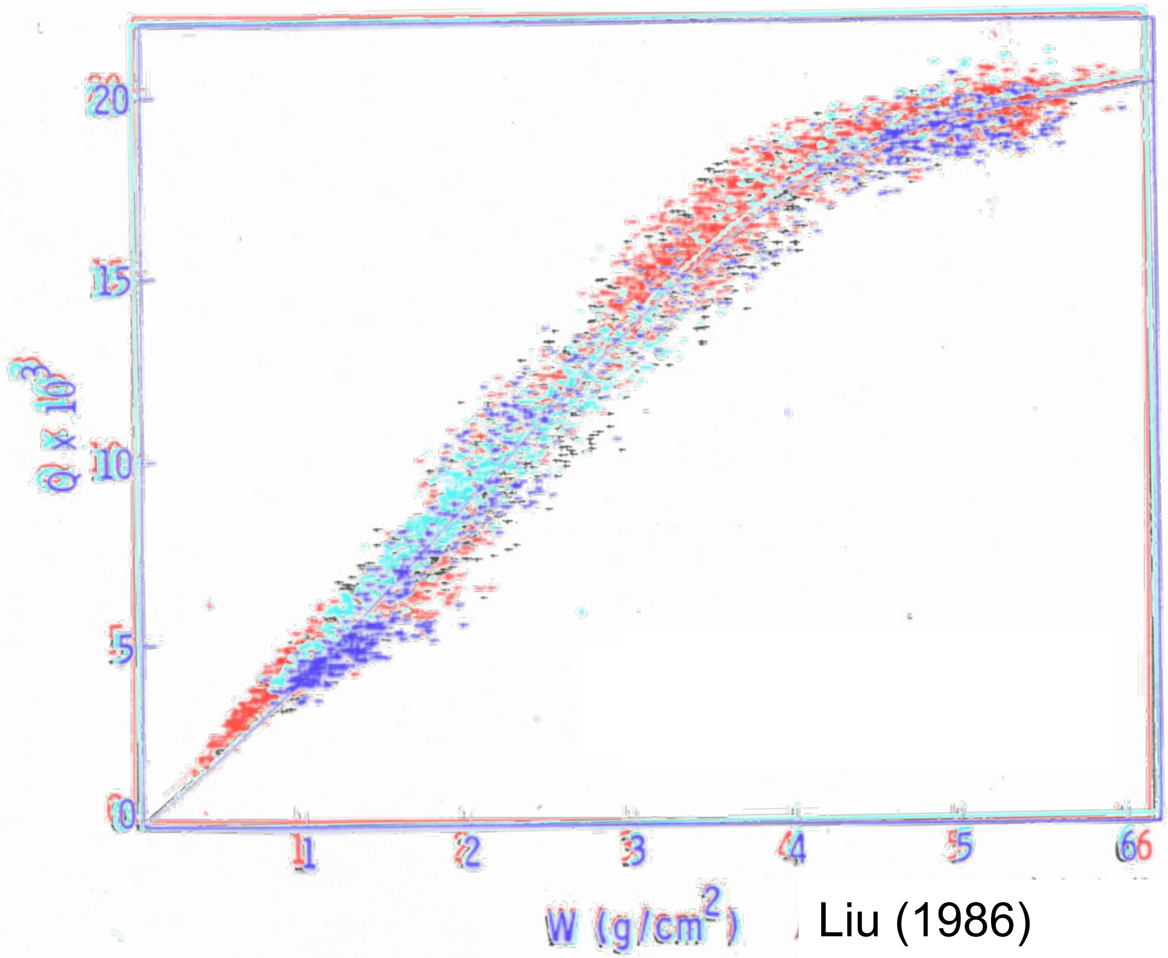


Rain extremes correlate with vertically integrated moisture transport but rainfall does not show the seasonal cycle of surface wind

Indian Ocean 6 stations 618 data records

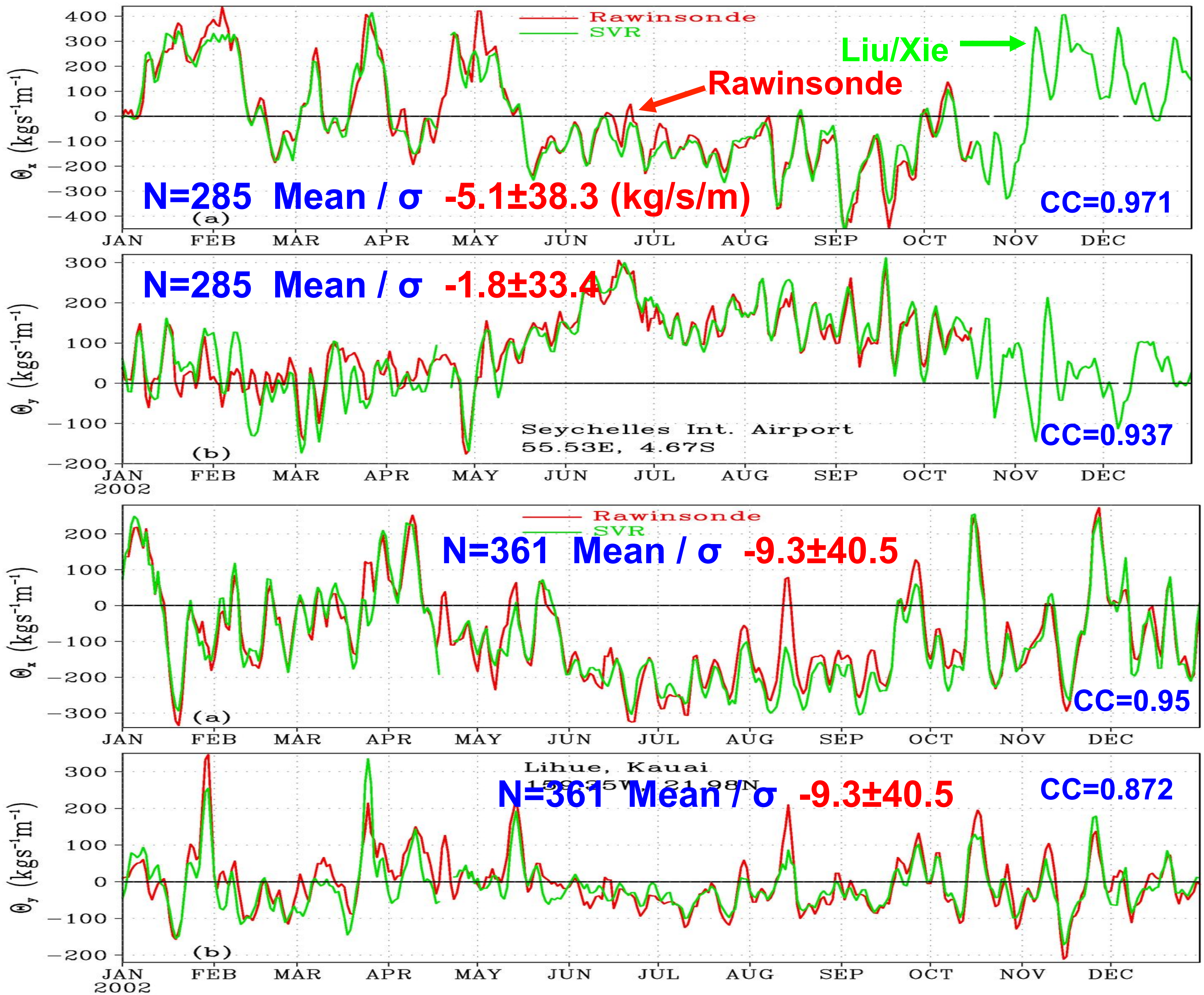
S. Pacific 6 Stations 855 data records

N. Pacific 14 Stations 1992 data records

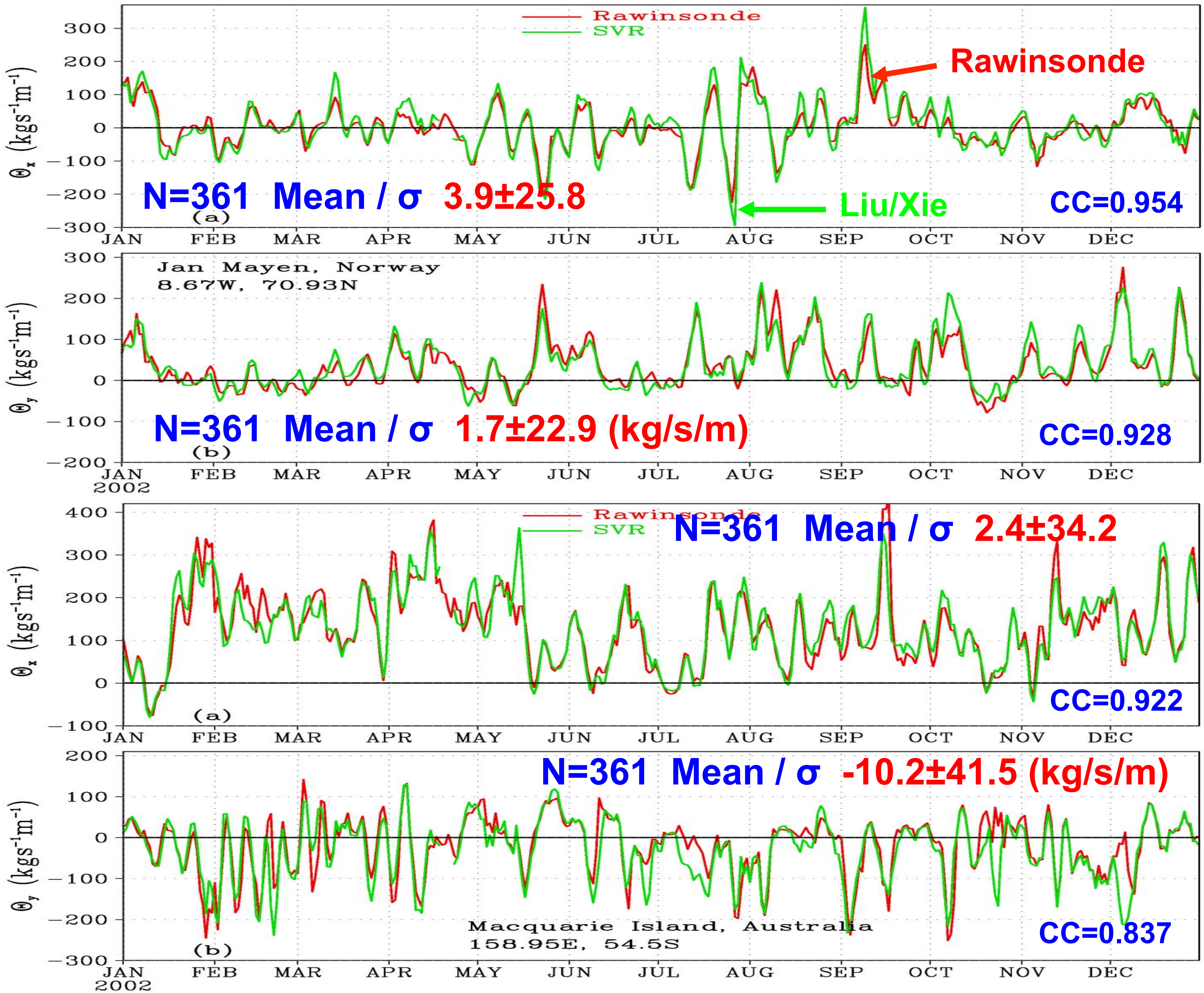


Liu (1986)

Atlantic 20 stations, 2161 data records



Rawinsonde
SVR
Liu/Xie
Rawinsonde
N=285 Mean / σ -5.1±38.3 (kg/s/m)
CC=0.971
(a)
Θ_x (kgs^{-1}m^{-1})
N=285 Mean / σ -1.8±33.4
Seychelles Int. Airport
55.53E, 4.67S
CC=0.937
(b)
Θ_y (kgs^{-1}m^{-1})
JAN 2002
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Rawinsonde
SVR
N=361 Mean / σ -9.3±40.5
CC=0.95
(a)
Θ_x (kgs^{-1}m^{-1})
Lihue, Kauai
159.35W, 21.98N
N=361 Mean / σ -9.3±40.5
CC=0.872
(b)
Θ_y (kgs^{-1}m^{-1})



Rawinsonde
SVR
Rawinsonde
Liu/Xie
N=361 Mean / σ 3.9±25.8
CC=0.954
(a)
Jan Mayen, Norway
8.67W, 70.93N
N=361 Mean / σ 1.7±22.9 (kg/s/m)
CC=0.928
(b)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
2002
Rawinsonde
SVR
N=361 Mean / σ 2.4±34.2
CC=0.922
(a)
N=361 Mean / σ -10.2±41.5 (kg/s/m)
Macquarie Island, Australia
158.95E, 54.5S
CC=0.837
(b)
Θx (kgs-1m-1)
Θy (kgs-1m-1)