Indian Monsoon in Oceanic and Terrestrial Water Balances

-characterize pre-monsoon drought and postulate its oceanic origin

W. Timothy Liu and Xiaosu Xie
Jet Propulsion Laboratory

- Aqarius Meeting in Buenos Aires, 11/18/2015

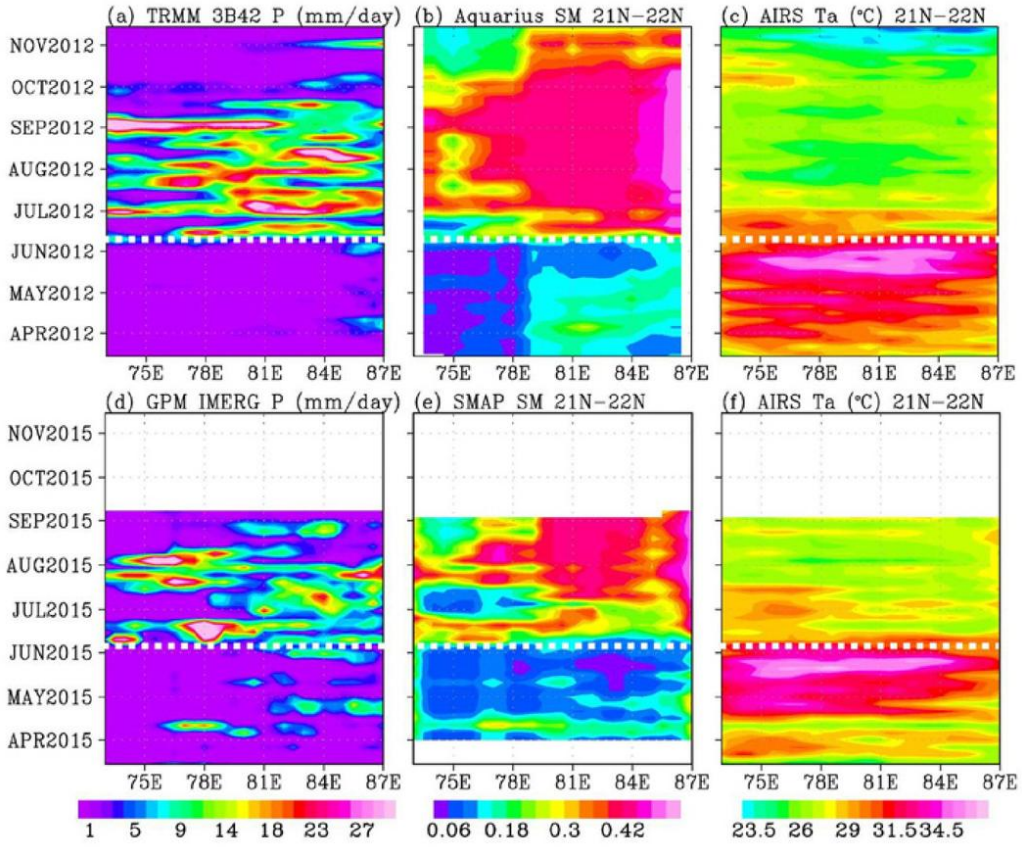
India heat wave kills 2,330 people as millions wait for rain

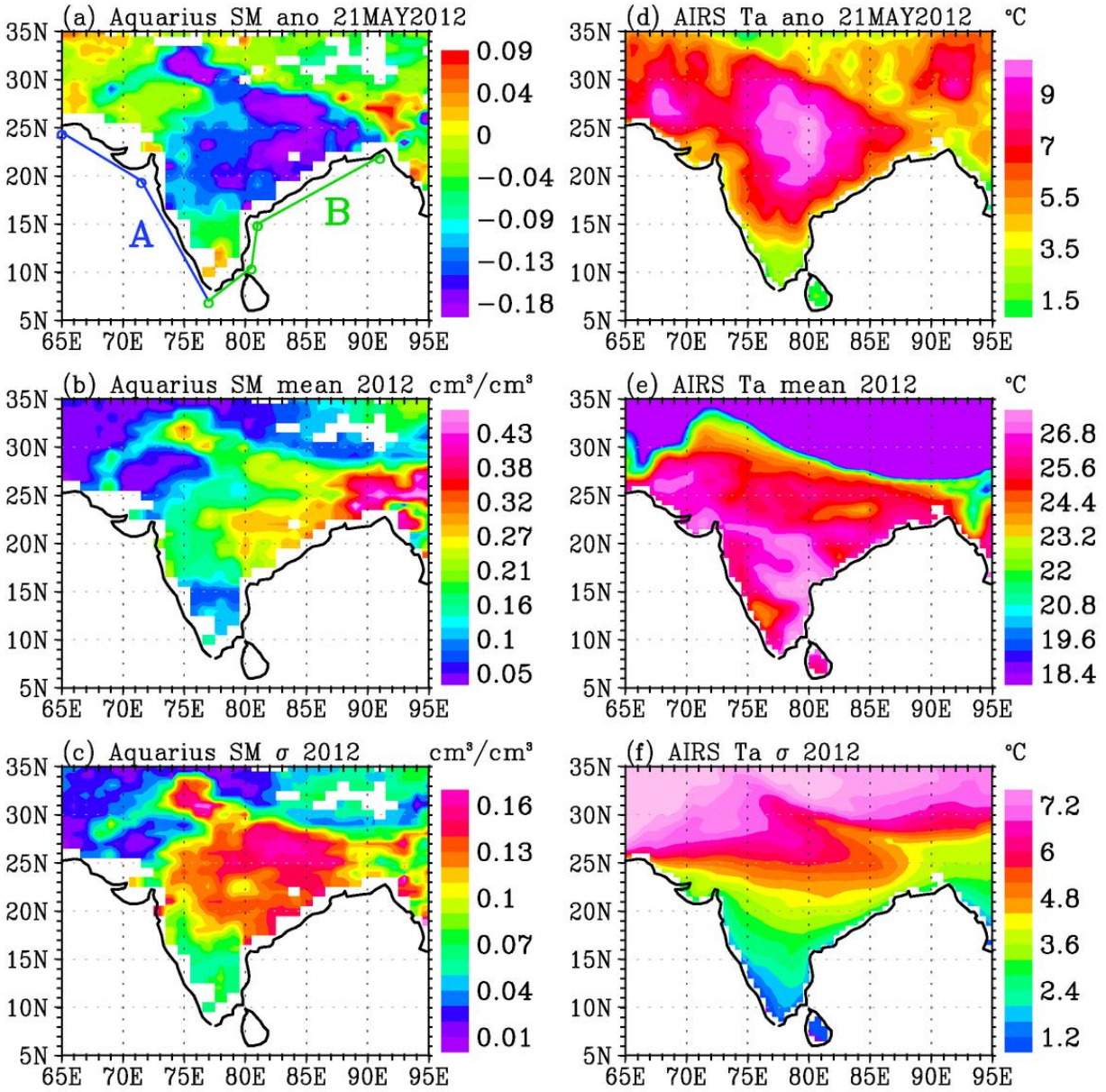
By Hilary Whiteman, CNN Updated 12:17 AM ET, Tue June 2, 2015 | Video Source: CNN

- There have been anecdotic descriptions of extreme dry and hot weather before summer monsoon that causes economic hardship and human suffering in India, but little documentation on the severity and postulation on the scientific reason.
- Are they results of human anxiety caused by delays of monsoon onset?
- 3 years of Aquarius soil moisture are used with rain from TRMM-replaced by SMAP and GPM in 2015 for characterization

IMAGES | SEPTEMBER 11, 2015

Pre-Monsoon Drought and Heat Waves in India





Geographical variation of drought and heat wave. (a) Soil moisture anomaly (deviation from annual mean) for the 5-day average from May 21-25, 2012, (b) annual mean of 2012, and (c) standard deviation of 2012. (d)-(f) are the same as (a)-(c), except for air

HYDROLOGIC BALANCE

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

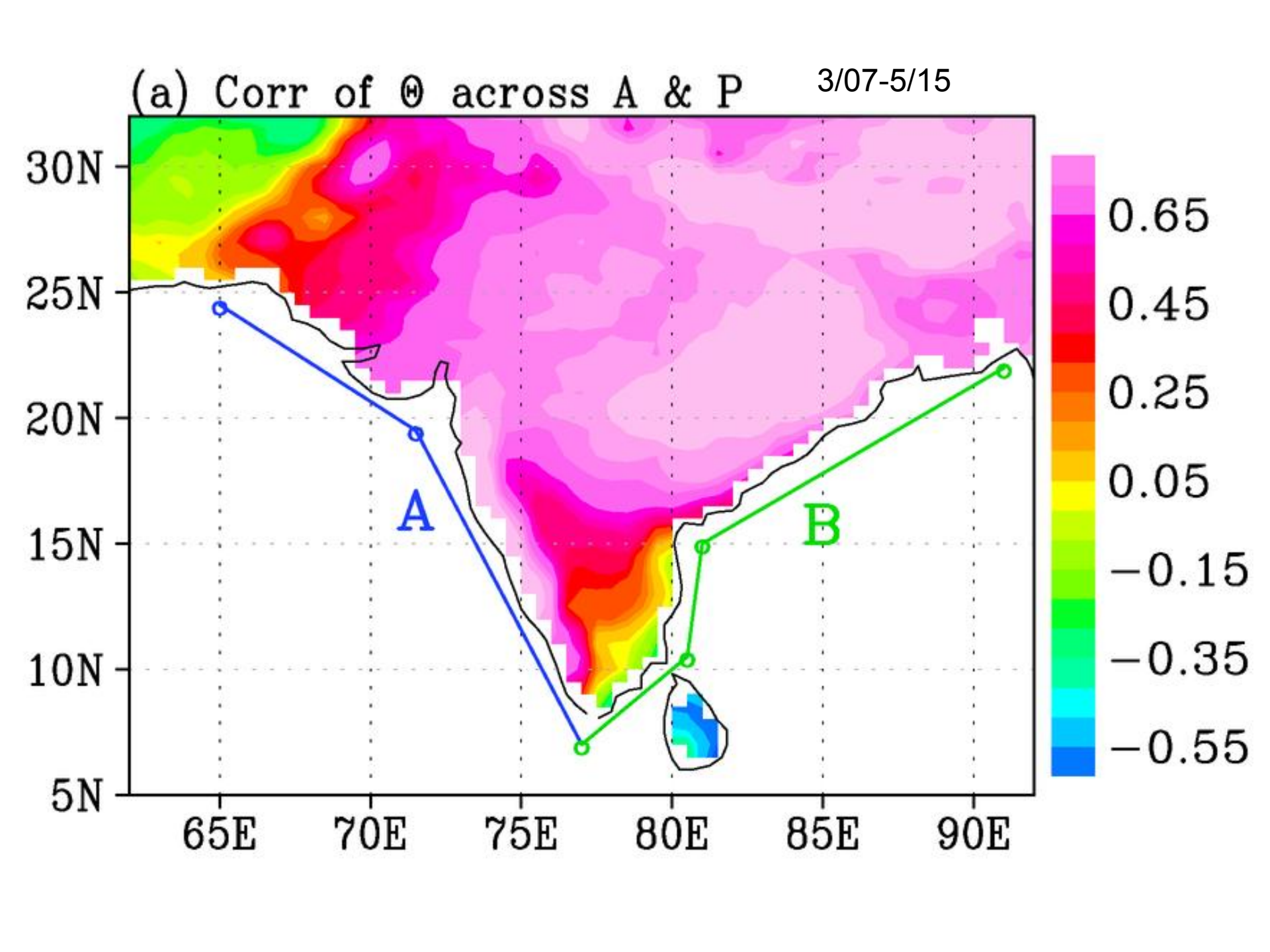
$$\Theta = \frac{1}{g}\int_0^{p0} qU\mathbf{d}p$$

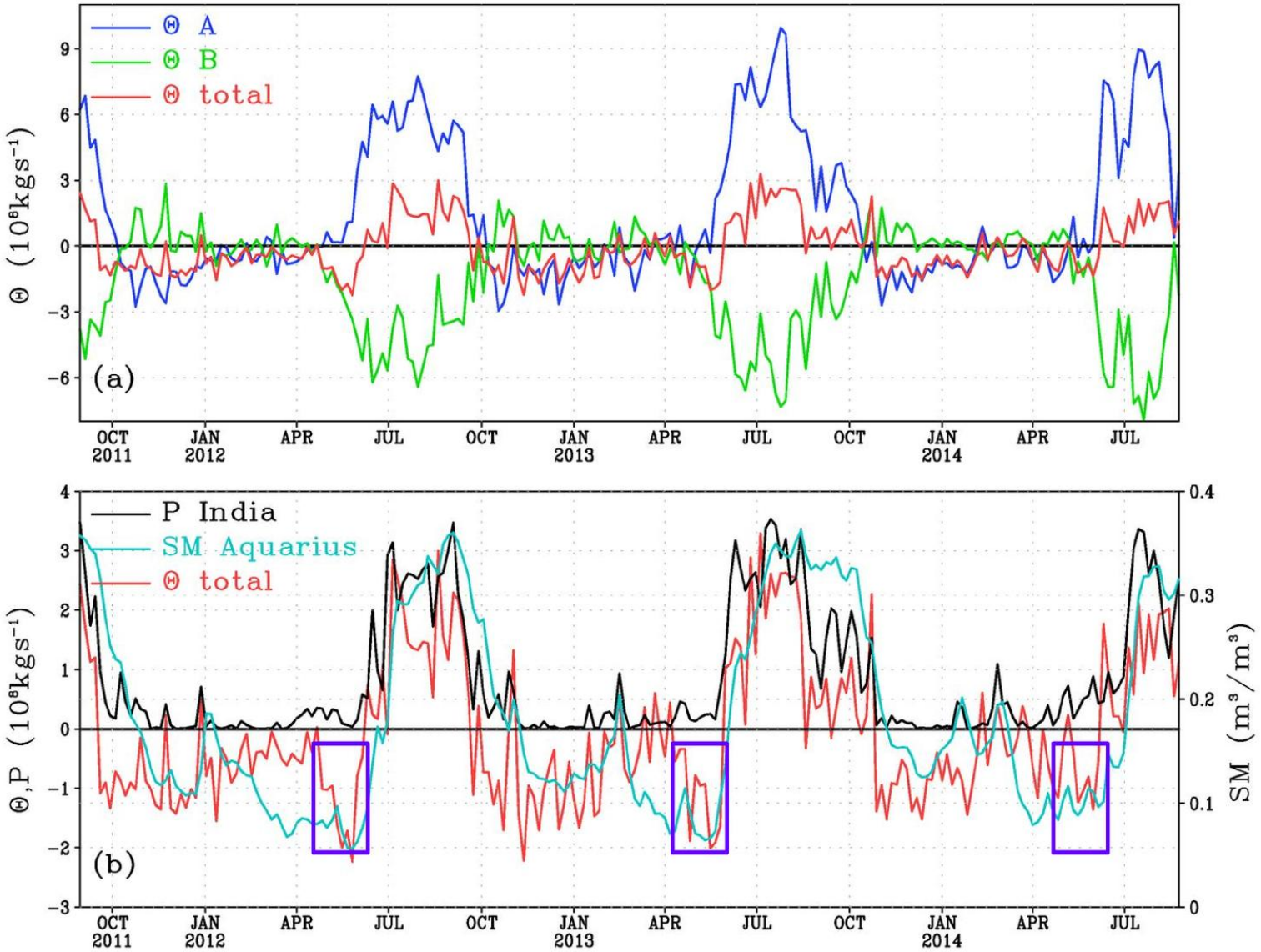
$$W = \frac{1}{g}\int_0^{p0} q\mathbf{d}p$$

$$\Theta = \mathbf{U}\mathbf{e}\, W$$

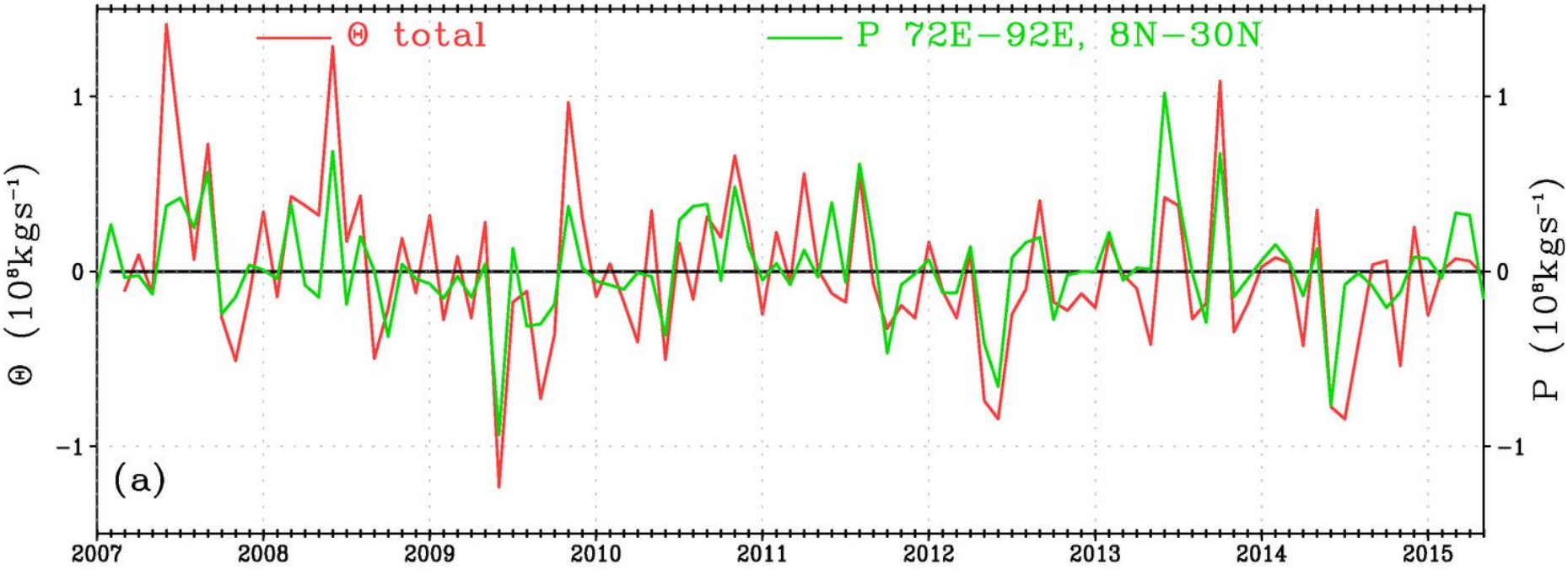
Θ is equivalent to column water vapor W advected by Ue.
Ue is the depth-averaged wind weighted by humidity
Before 2005, Ue is related to Un only
From 2005, We use SVR to relate Ue to wind at two levels:
1. U_N: scatterometer surface wind stress
2. U_{850mb}: cloud drift wind (free-stream wind)

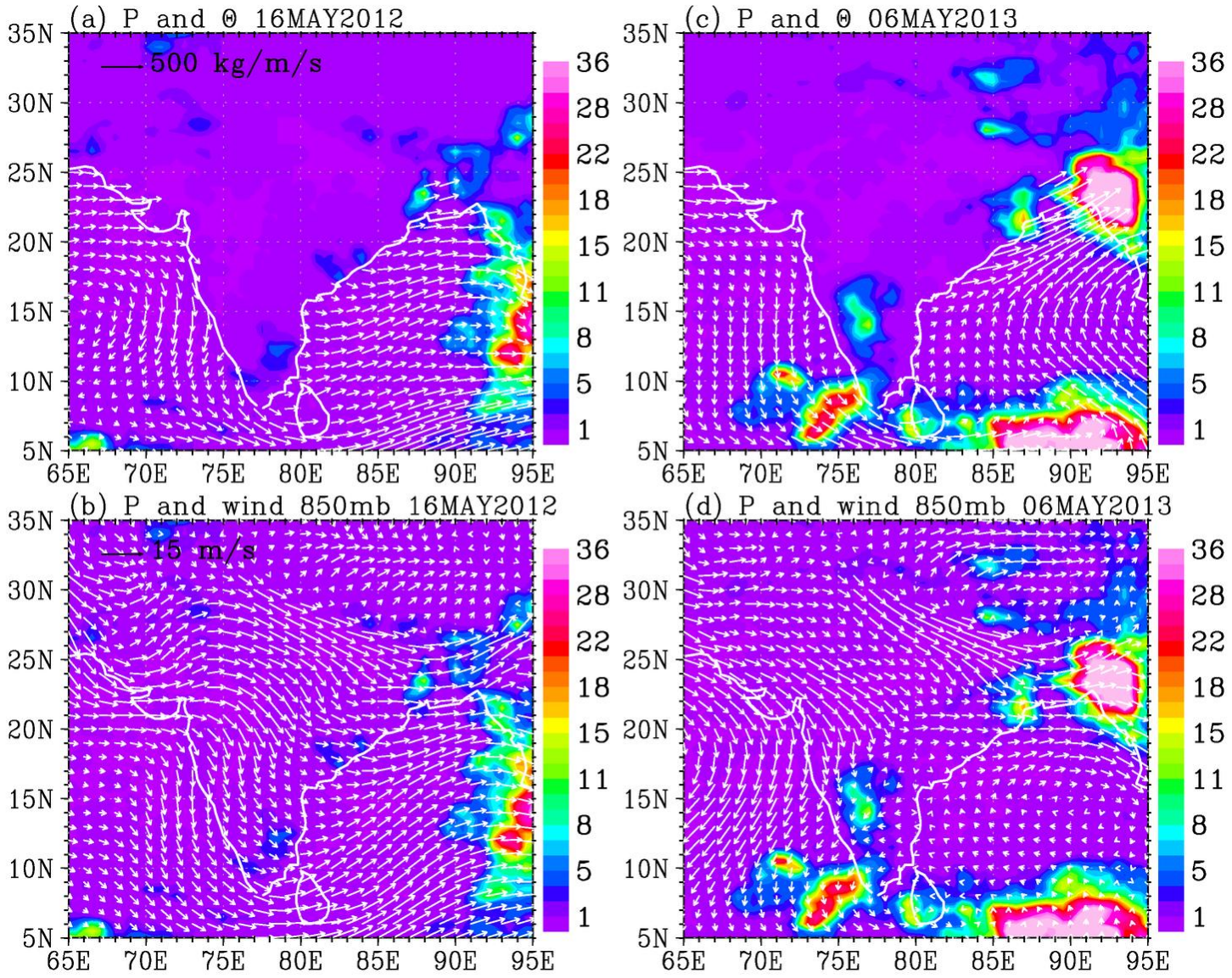
- Xie et al. [2008] show the model-derived Θ agree with Θ from 90 rawinsonde stations from synoptic to seasonal time scales and from equatorial to polar oceans.
- Hilburn [2010] found very good agreement between this data set and data computed from MERRA over the global ocean.
- Liu et al. 2006] showed closure the terrestrial water balance in South America.
- Liu et al. [2012] demonstrated the significance of Θ in affecting rainfall in West Africa where the surface winds are in different direction from winds aloft.
- Liu and Xie [2014] (Enclycopedia of Remote Sensing)summarize valiation and application, showing water balance over global ocean and major continents


(a) Corr of Θ across A & P
3/07-5/15
30N
25N
20N
15N
10N
5N
65E
70E
75E
80E
85E
90E
A
B
0.65
0.45
0.25
0.05
−0.15
−0.35
−0.55

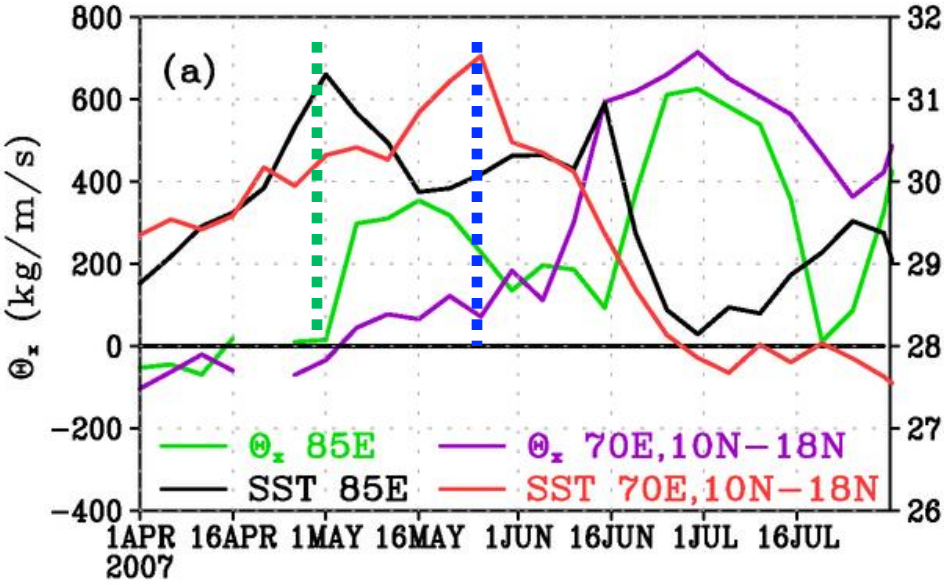


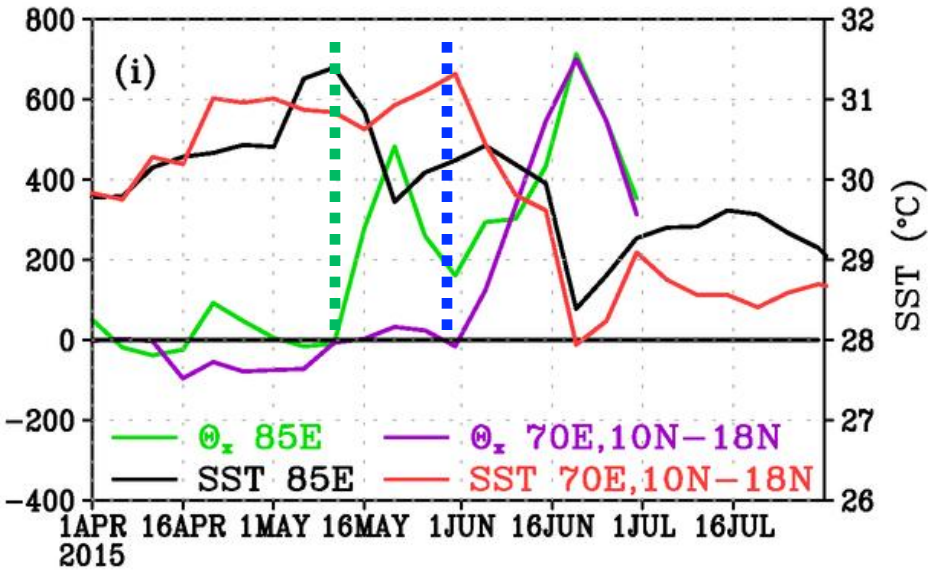
Indian Monsoon as described by integrated moisture transport (Θ). (a) Three year time series of Θ from Arabian Sea to land integrated along coastline A (blue),l Θ from Bay of Bengal to land integrated along coastline B (green), positive for onshore flow, and the net transport to land (red). (b) Time series of precipitation sum (black) and average soil moisture (cyan) over the Indian subcontinent between 72°E-85°E and 10°N-30°N, and net Θ (red). Coastline A and B are delineated in the map of Fig. 2(a).

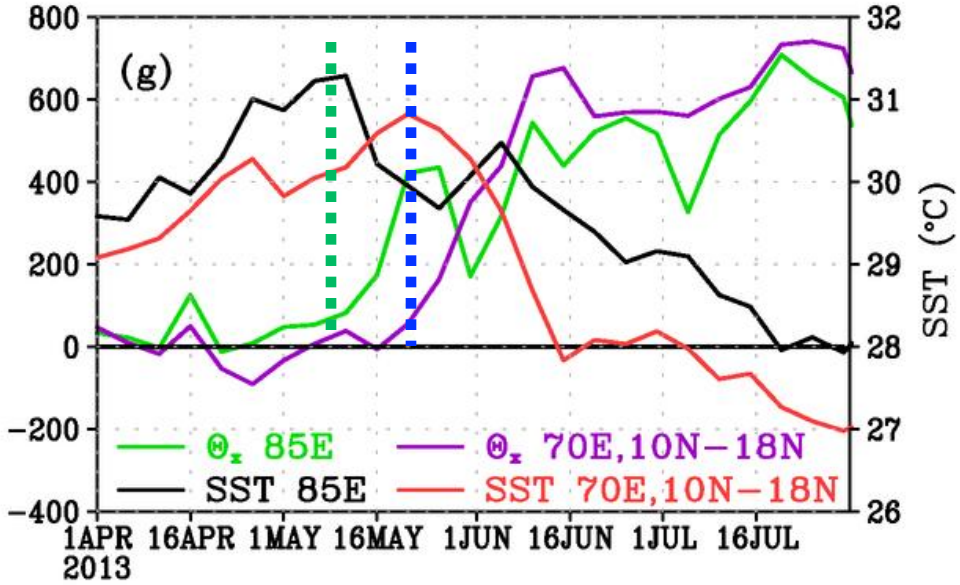

Θ total
P 72E−92E, 8N−30N
Θ (10⁸kgs⁻¹)
P (10⁸kgs⁻¹)
1
0
−1
(a)
2007
2008
2009
2010
2011
2012
2013
2014
2015



Atmospheric transports during pre-monsoon drought. (a) **Θ** and (b) 850 mb wind, averaged between May 16-20, 2012, both represented by white arrows, superimposed by precipitation in color. (c) and (d) are the same as (a) and (b), except for May 6-10, 2013.







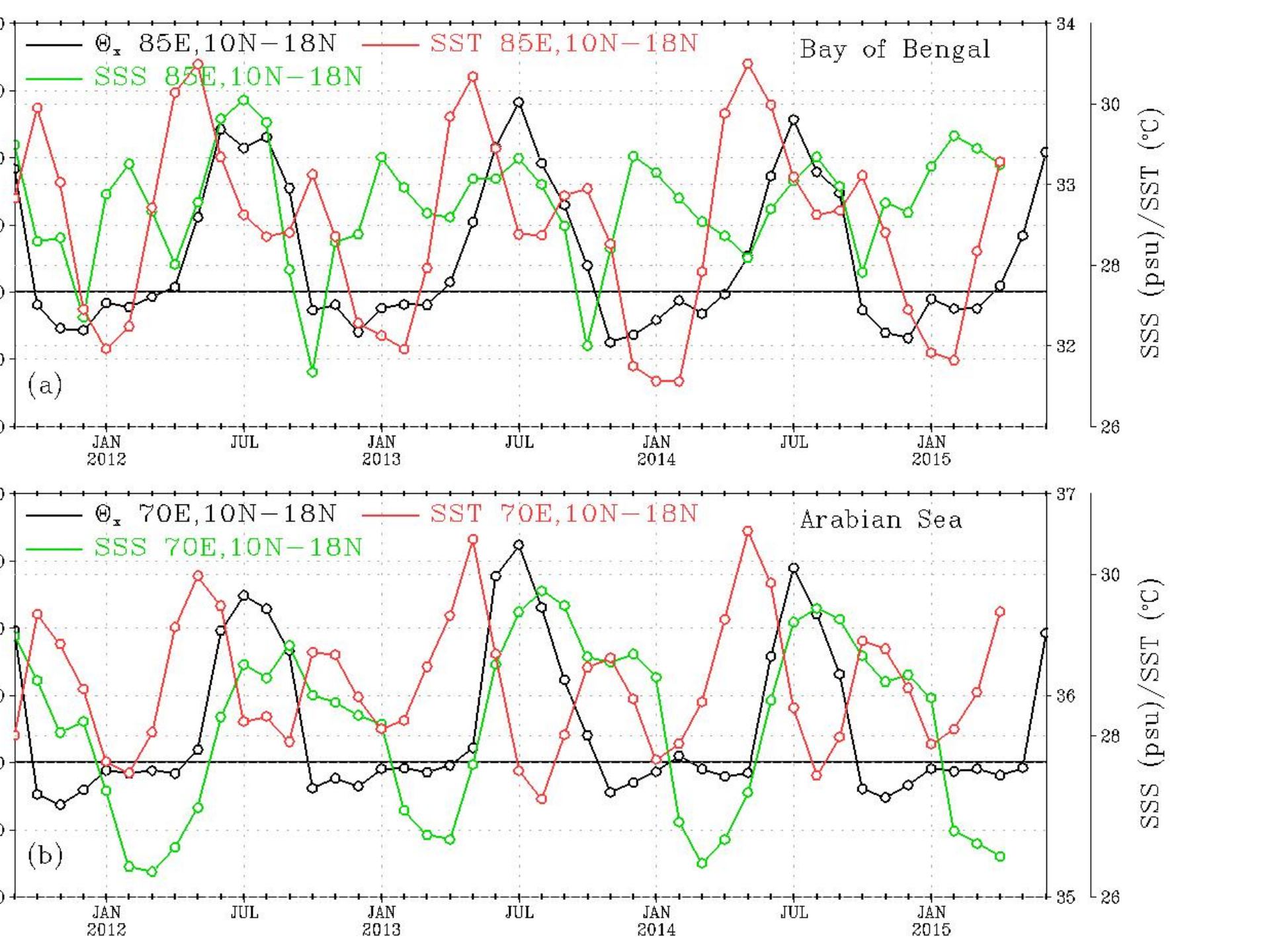
Green – Zonal transport in BB

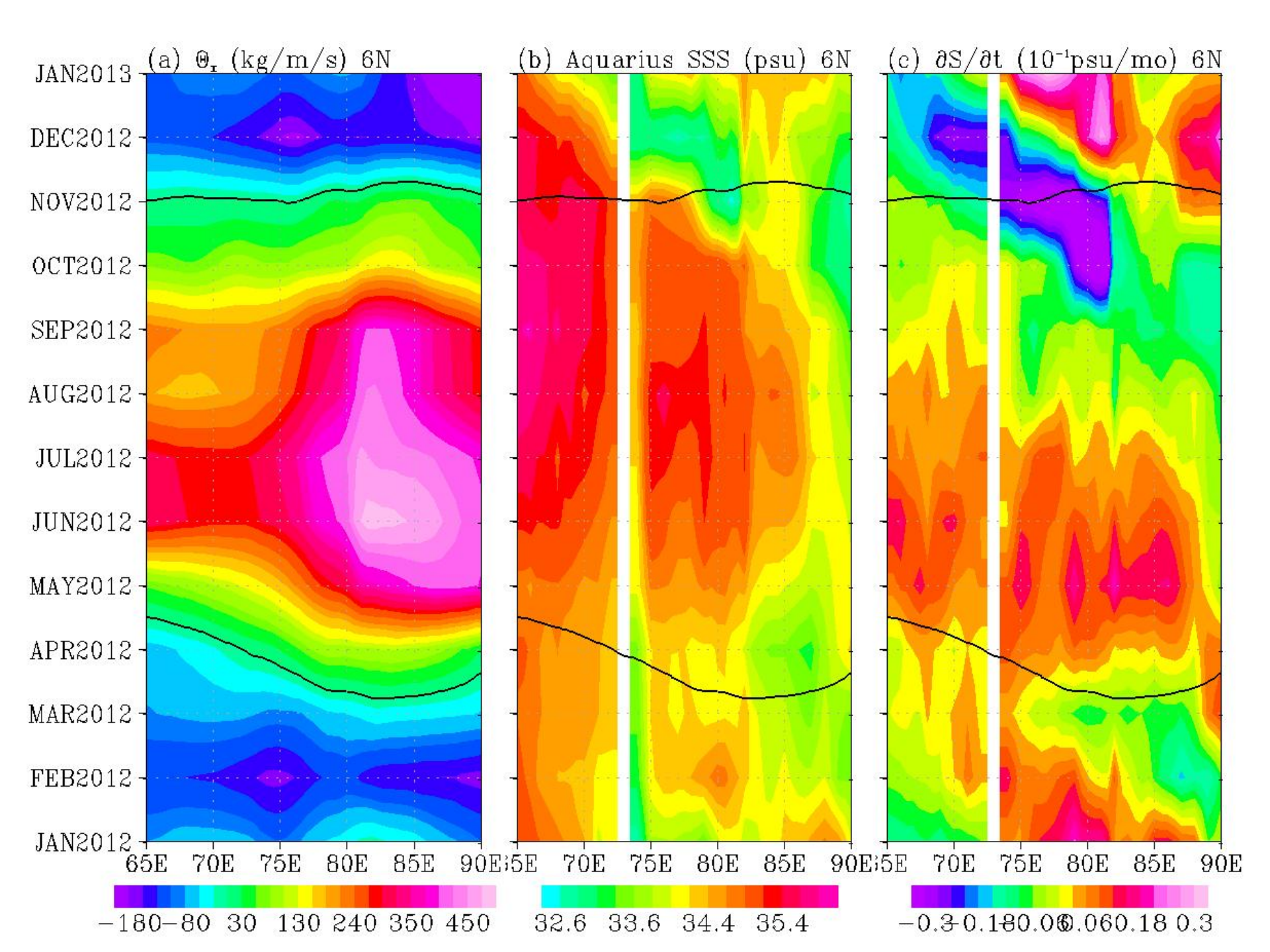
Purple – Zonal transport in AS

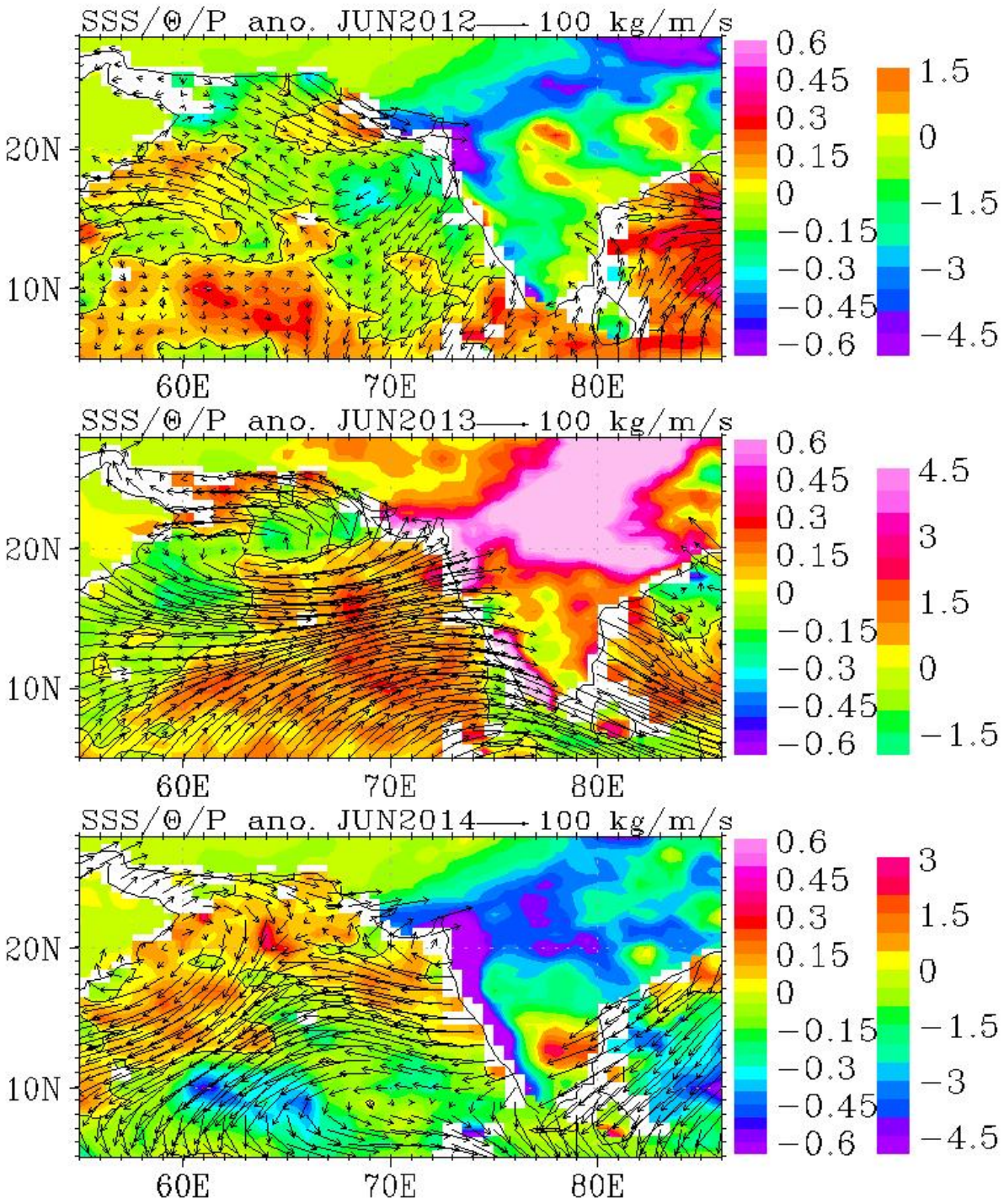
Black – SST in BB

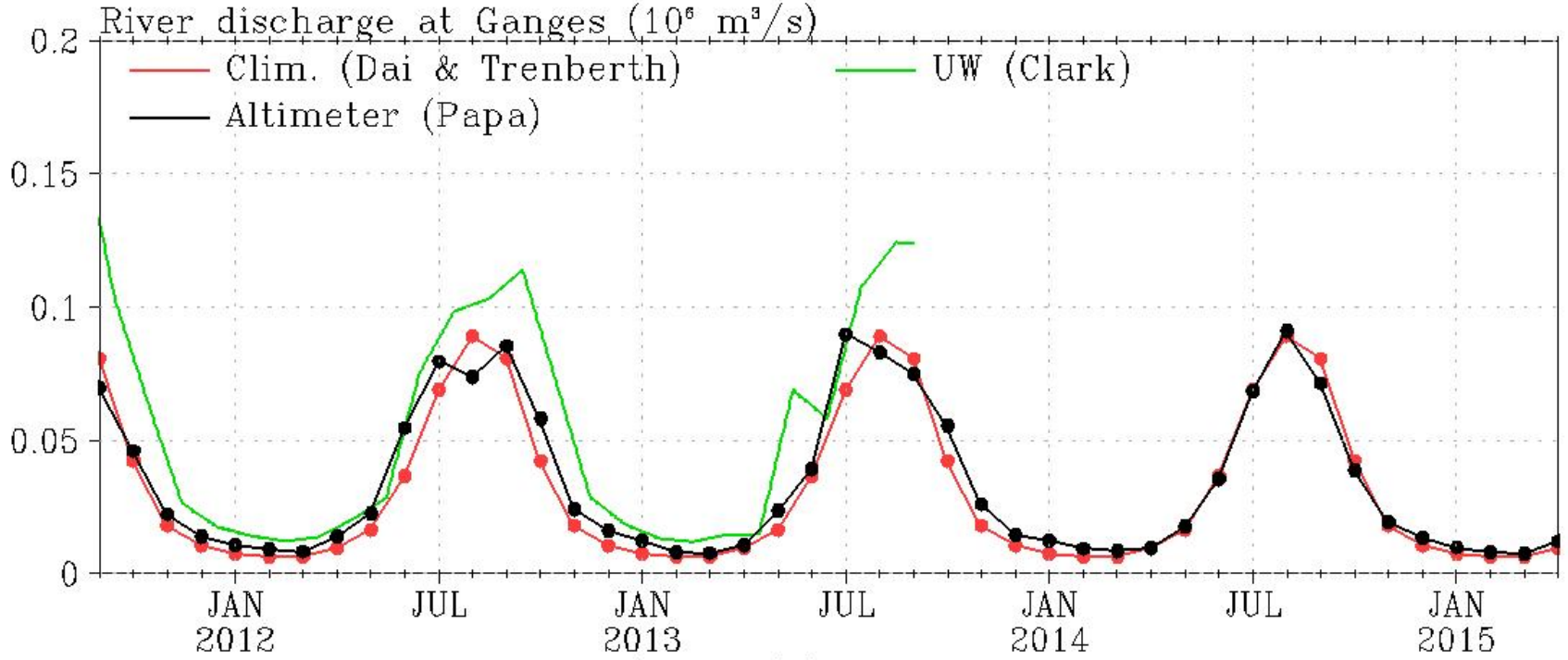
Red – SST in AS

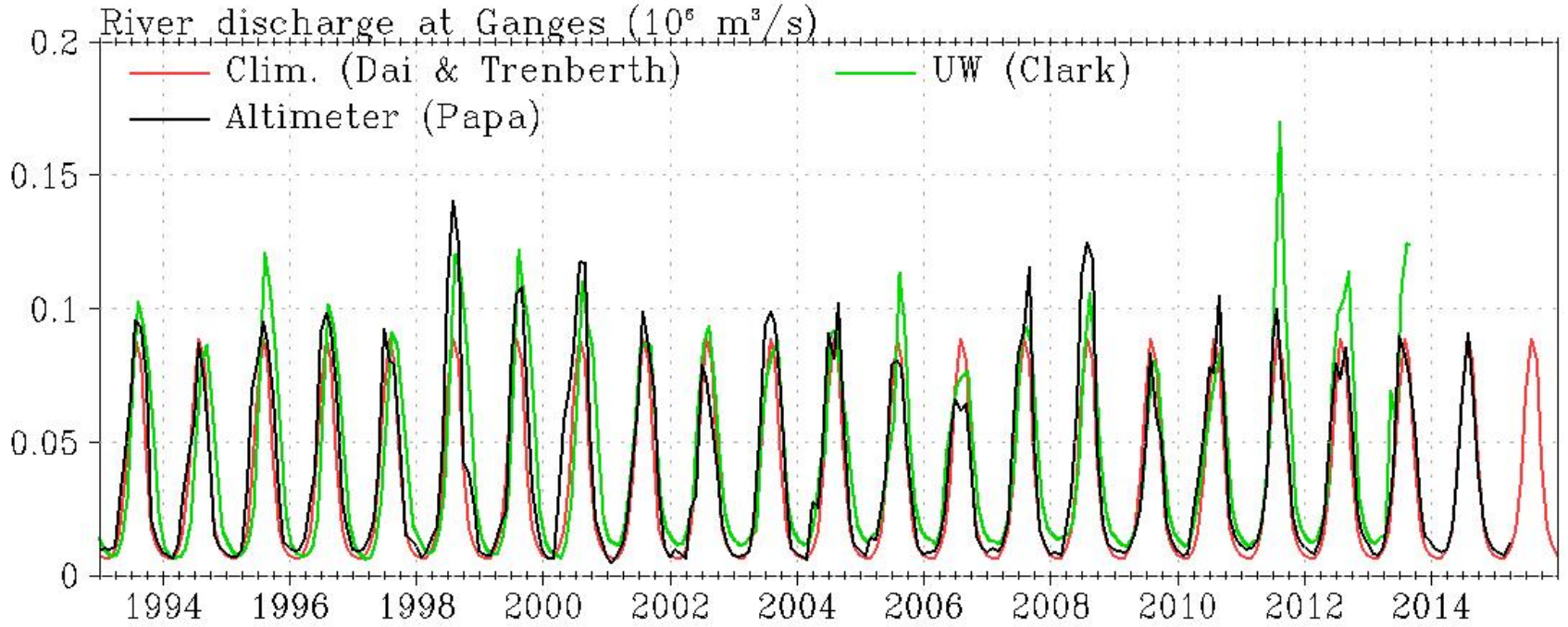
Summer monsoon starts at the peak of SST rise, in both AS and BB. BS changes earlier than AS


Θx 85E,10N−18N
SST 85E,10N−18N
SSS 85E,10N−18N
Bay of Bengal
(a)
SSS (psu)/SST (°C)
JAN 2012
JUL
JAN 2013
JUL
JAN 2014
JUL
JAN 2015
Θx 70E,10N−18N
SST 70E,10N−18N
SSS 70E,10N−18N
Arabian Sea
(b)
SSS (psu)/SST (°C)

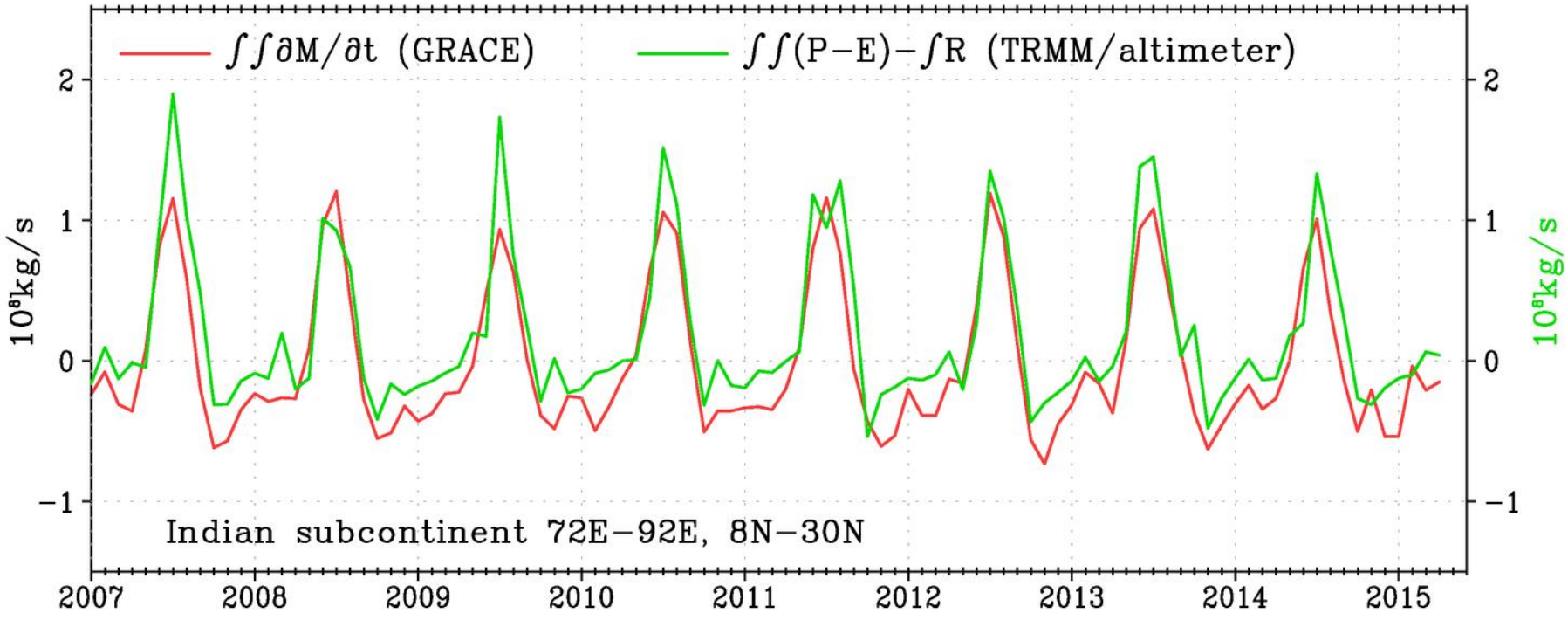

(a) Θx (kg/m/s) 6N
(b) Aquarius SSS (psu) 6N
(c) ∂S/∂t (10⁻¹psu/mo) 6N
JAN2013
DEC2012
NOV2012
OCT2012
SEP2012
AUG2012
JUL2012
JUN2012
MAY2012
APR2012
MAR2012
FEB2012
JAN2012
65E 70E 75E 80E 85E 90E
−180 −80 30 130 240 350 450
32.6 33.6 34.4 35.4
−0.3 −0.18 −0.06 0.06 0.18 0.3

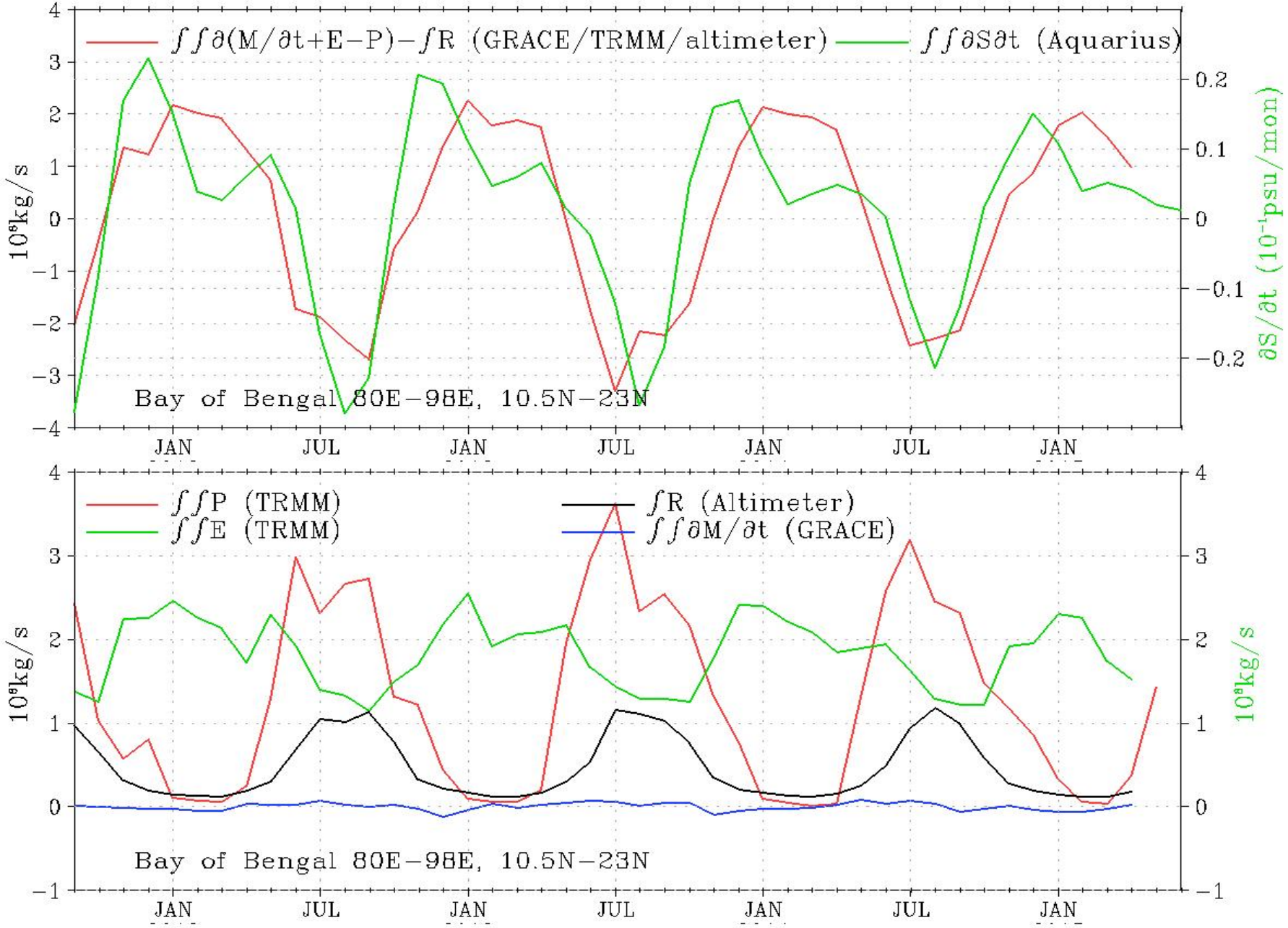

SSS/Θ/P ano. JUN2012
100 kg/m/s
0.6
0.45
0.3
0.15
0
−0.15
−0.3
−0.45
−0.6
1.5
0
−1.5
−3
−4.5
20N
10N
60E
70E
80E
SSS/Θ/P ano. JUN2013
100 kg/m/s
0.6
0.45
0.3
0.15
0
−0.15
−0.3
−0.45
−0.6
4.5
3
1.5
0
−1.5
20N
10N
60E
70E
80E
SSS/Θ/P ano. JUN2014
100 kg/m/s
0.6
0.45
0.3
0.15
0
−0.15
−0.3
−0.45
−0.6
3
1.5
0
−1.5
−3
−4.5
20N
10N
60E
70E
80E


River discharge at Ganges (10⁶ m³/s)
Clim. (Dai & Trenberth)
Altimeter (Papa)
UW (Clark)
0.2
0.15
0.1
0.05
0
JAN 2012
JUL
JAN 2013
JUL
JAN 2014
JUL
JAN 2015


River discharge at Ganges (10⁶ m³/s)
Clim. (Dai & Trenberth)
Altimeter (Papa)
UW (Clark)
0.2
0.15
0.1
0.05
0
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

Continental Closure at Seasonal Time Scale



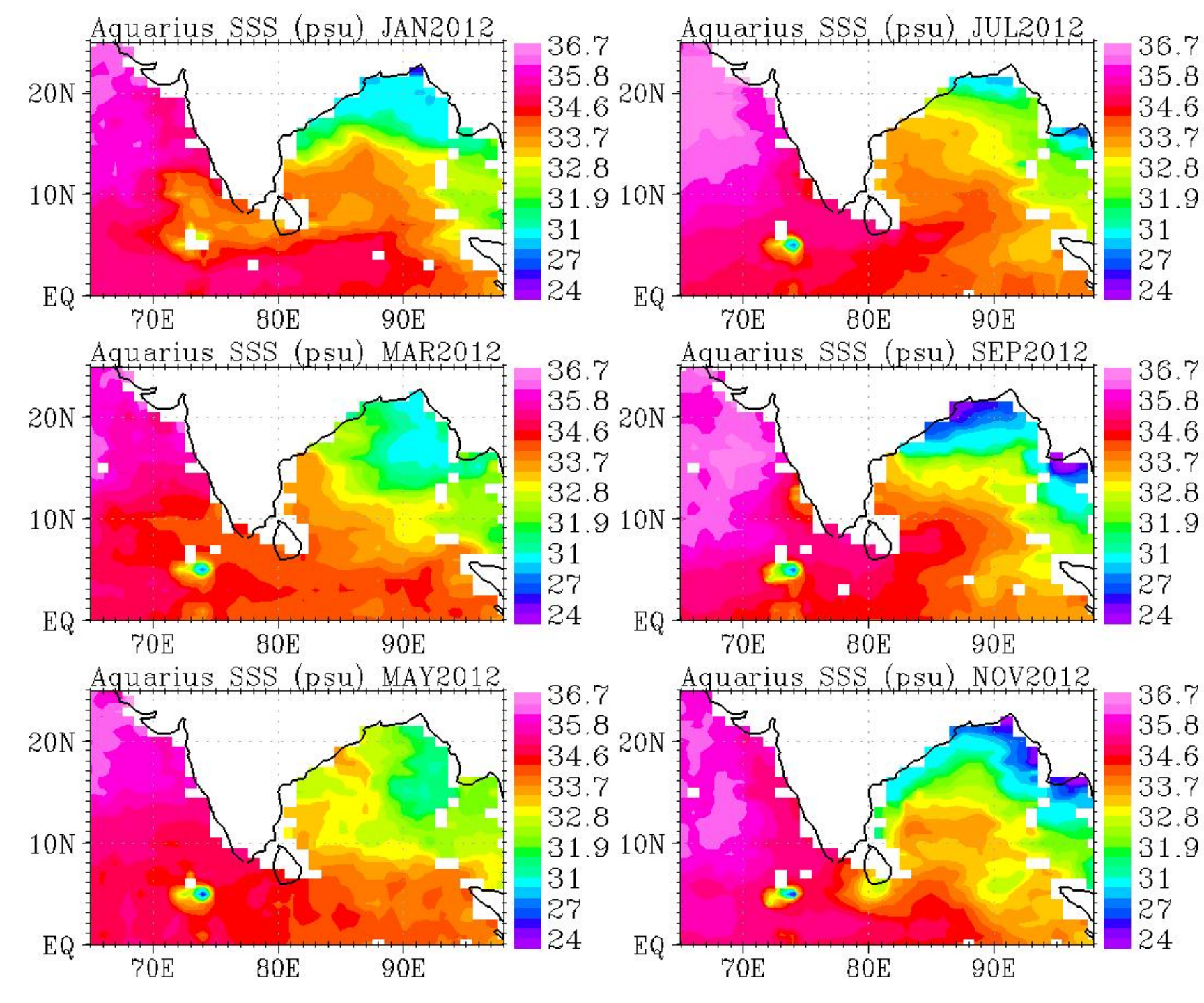


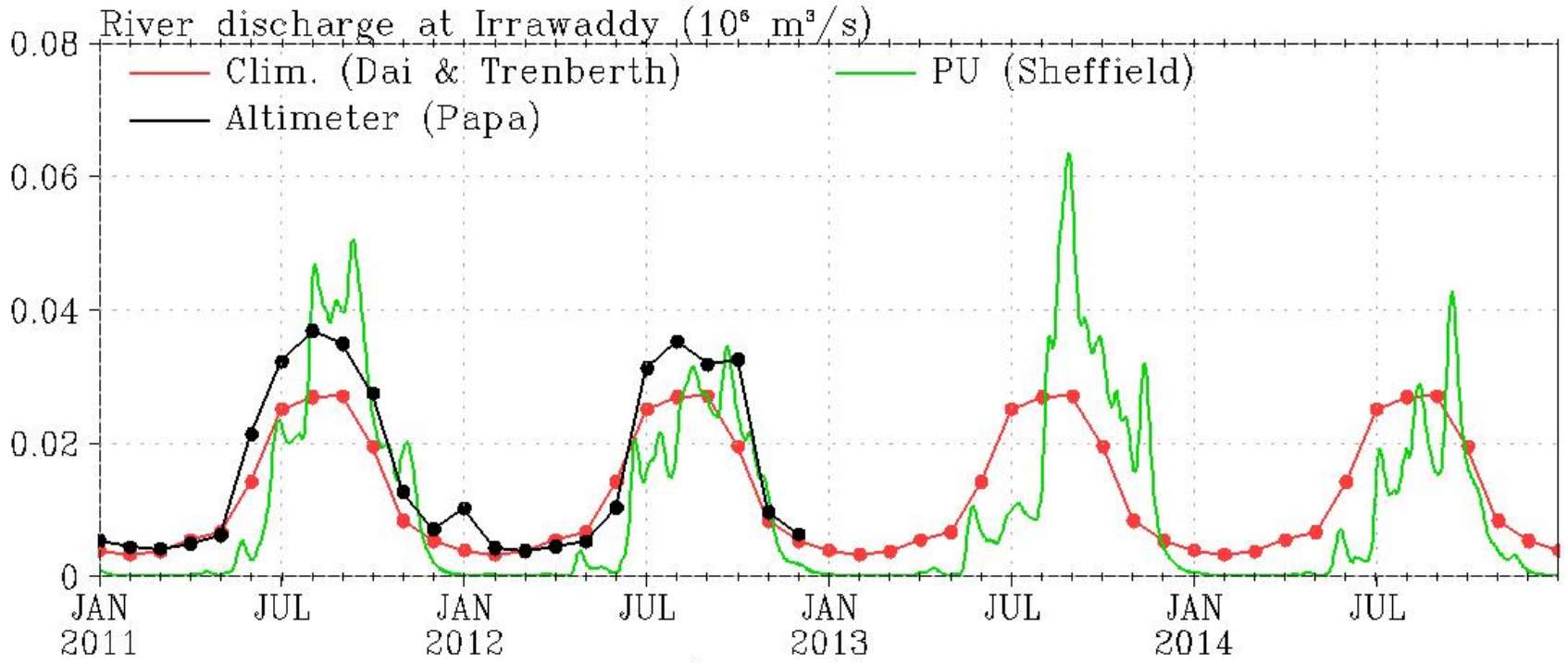
Residual of mass balance reveals transport from equatorial ocean

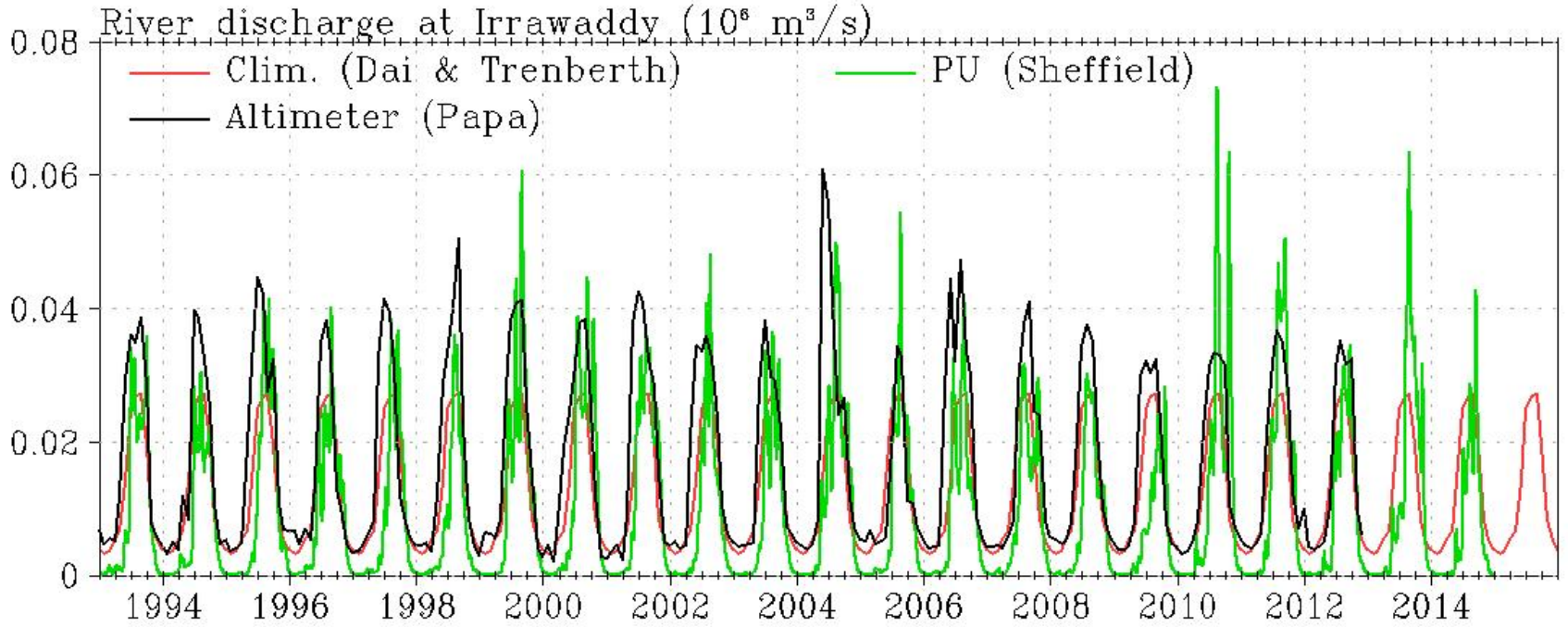
Summary

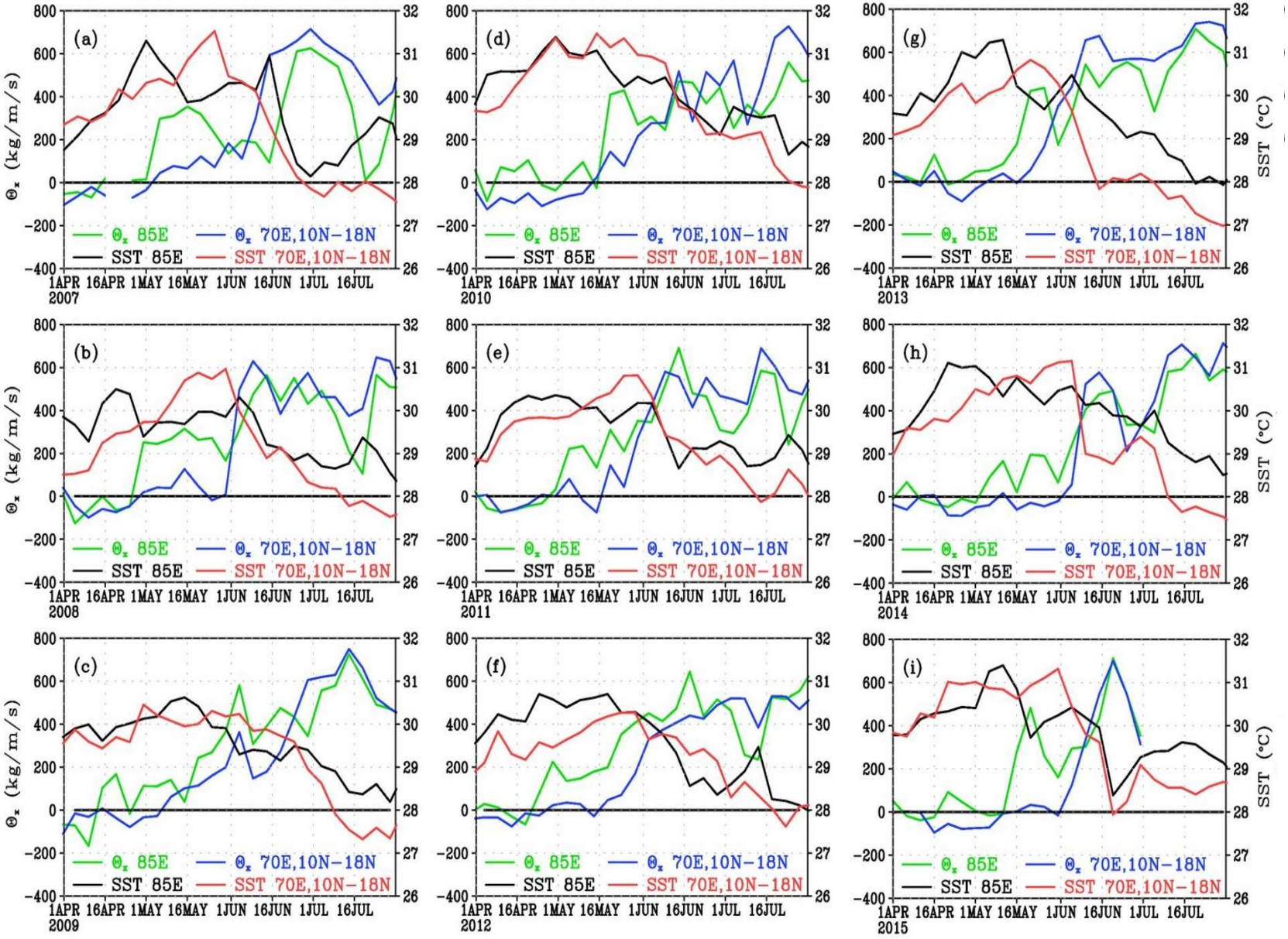
- L-band radiometers allows us to characterize pre-monsoon drought (PMD).
- PMD is an annual occurrence, may be amplified by interannual variation of monsoon onset but not driven by it.
- It occurs when moisture advects out to BB earlier than coming in from AS.
- Southwest summer monson starts earlier in BB and sucks air out of India, replaced by air from the NW desert before monsoon moisture comes from AS
- Summer monsoon is found to start at the peak of sea surface temperature (SST) rise in both AS and BB
- SST rise preceeds BB monsoon onset allowing early warning of drought, mitigating human and economic adversaries
- Ocean currents that cause annual temperture and salinity cycle in AS and BB are not driven by local monsoon
- How they are remotely generated remain unclear.
- We are examining river discharges (from land surface model and alitmeter), evapotranspiration over land, mass changes over land and ocean (GRACE). The water budget and deviation from closure would shed new lights on the linkage of ocean and terrestrial water cycles.

backup


Aquarius SSS (psu) JAN2012
Aquarius SSS (psu) JUL2012
Aquarius SSS (psu) MAR2012
Aquarius SSS (psu) SEP2012
Aquarius SSS (psu) MAY2012
Aquarius SSS (psu) NOV2012
20N
10N
EQ
70E
80E
90E
36.7
35.8
34.6
33.7
32.8
31.9
31
27
24


River discharge at Irrawaddy (10⁶ m³/s)
Clim. (Dai & Trenberth)
Altimeter (Papa)
PU (Sheffield)
0.08
0.06
0.04
0.02
0
JAN
2011
JUL
JAN
2012
JUL
JAN
2013
JUL
JAN
2014
JUL

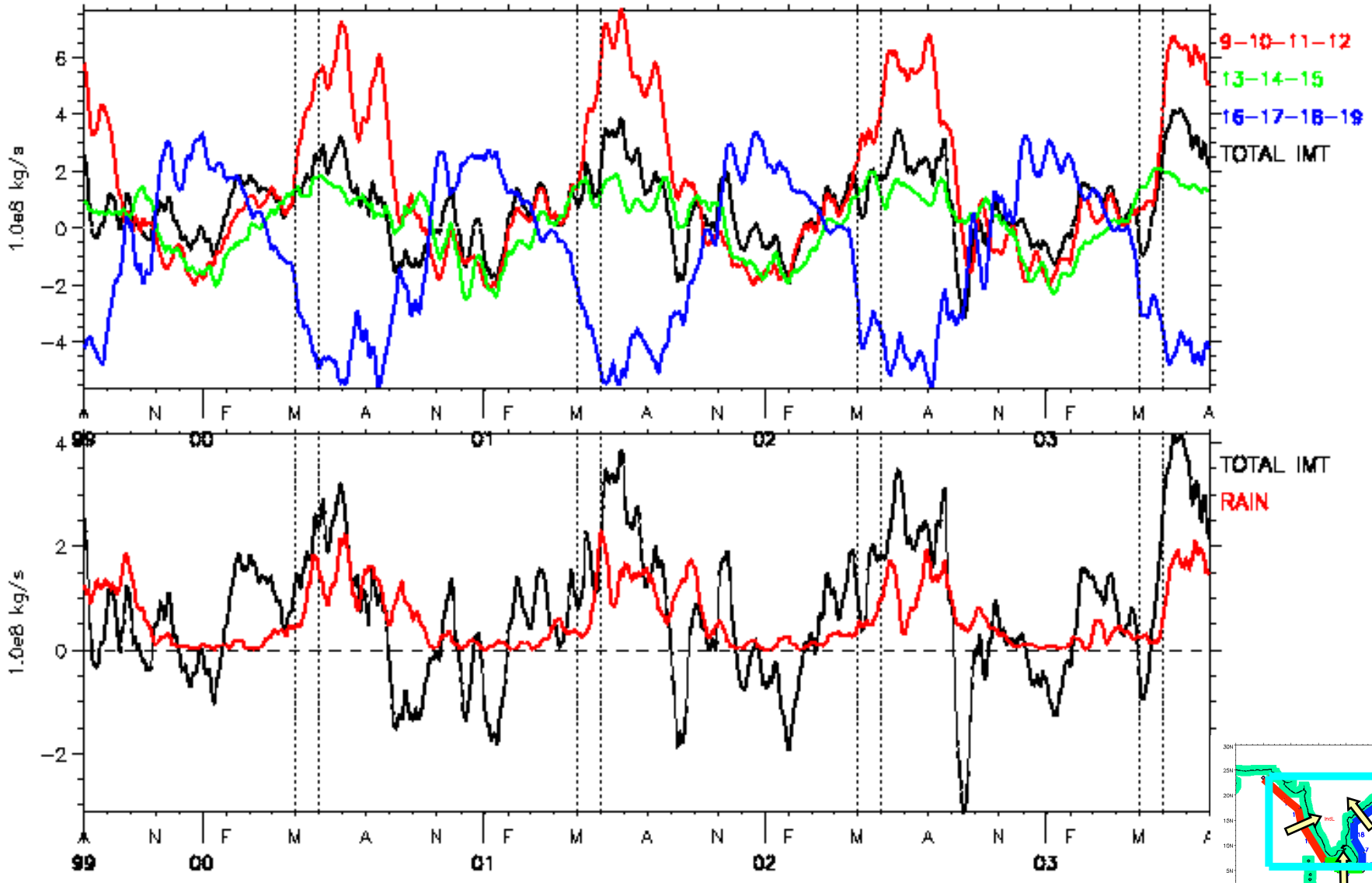

River discharge at Irrawaddy (10⁶ m³/s)
Clim. (Dai & Trenberth)
Altimeter (Papa)
PU (Sheffield)
0.08
0.06
0.04
0.02
0
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

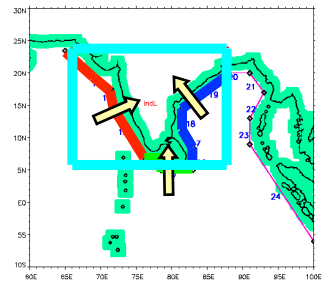


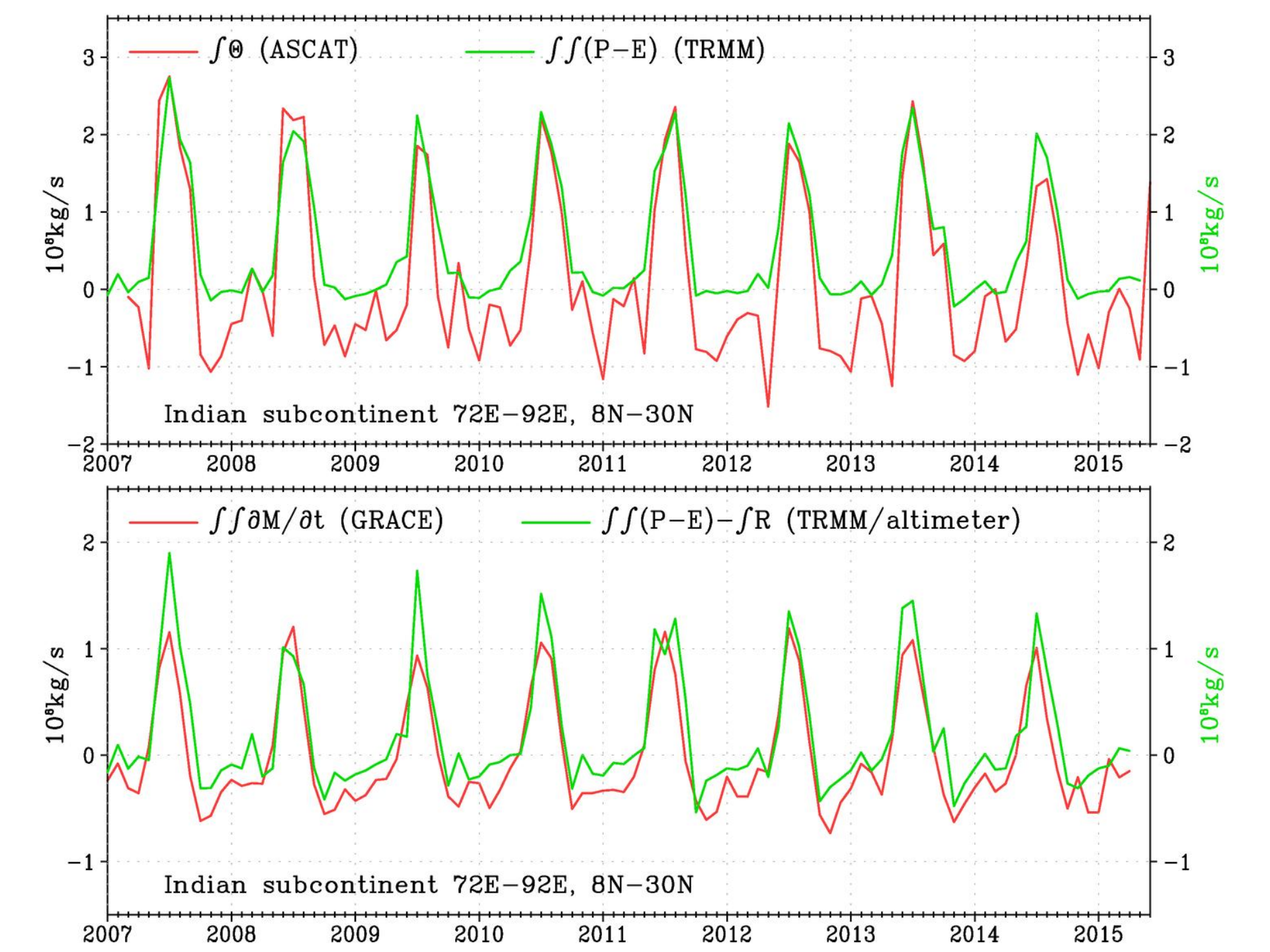
Comparing summer monsoon onsets in Arabian Sea and Bay of Bengal. Θ (green) and SST (black) averaged from 10ºN-18ºN along 85ºE in the Bay of Bengal, compared with Θ (blue) and SST (red) averaged from 10ºN-18ºN along 70ºE in the Arabian Sea, between April and July for 2007 to 2015 (a to i).

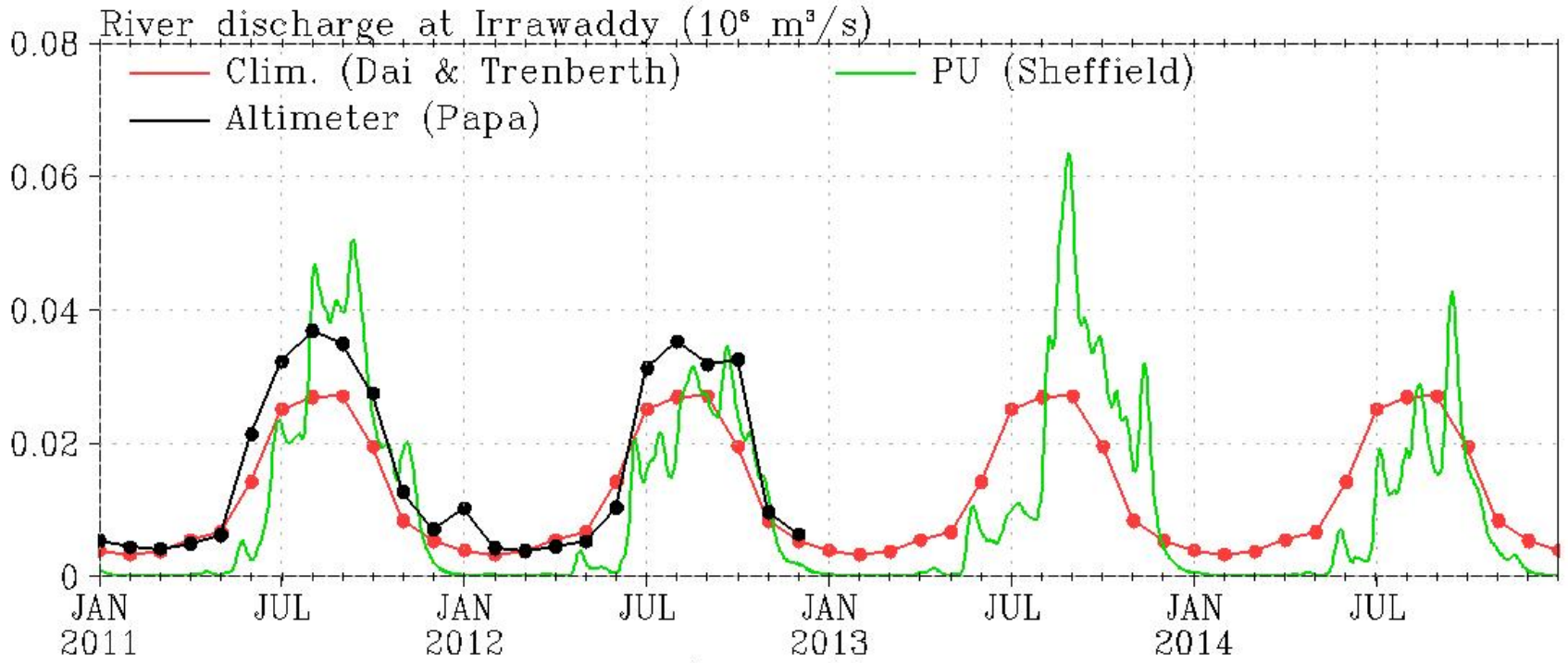
Integrated moisture transport and rainfall over India continent

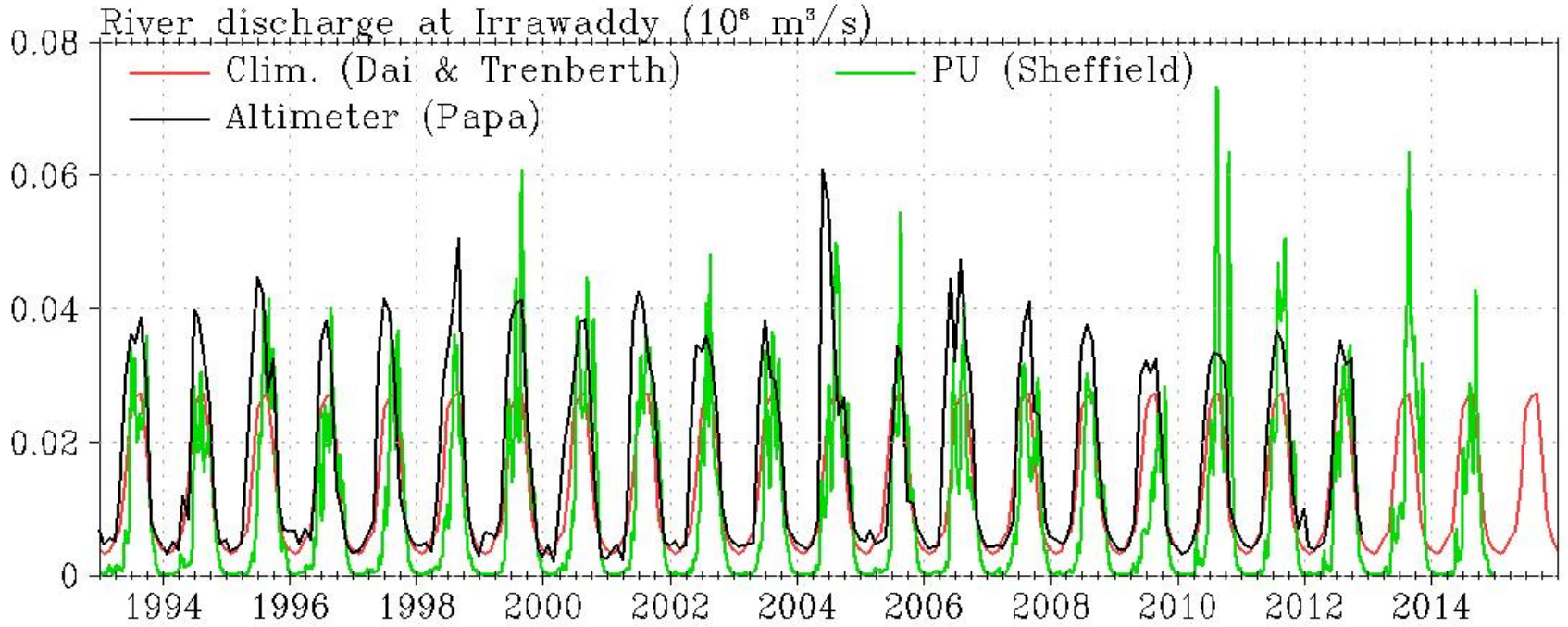
Liu and Tang, 2004

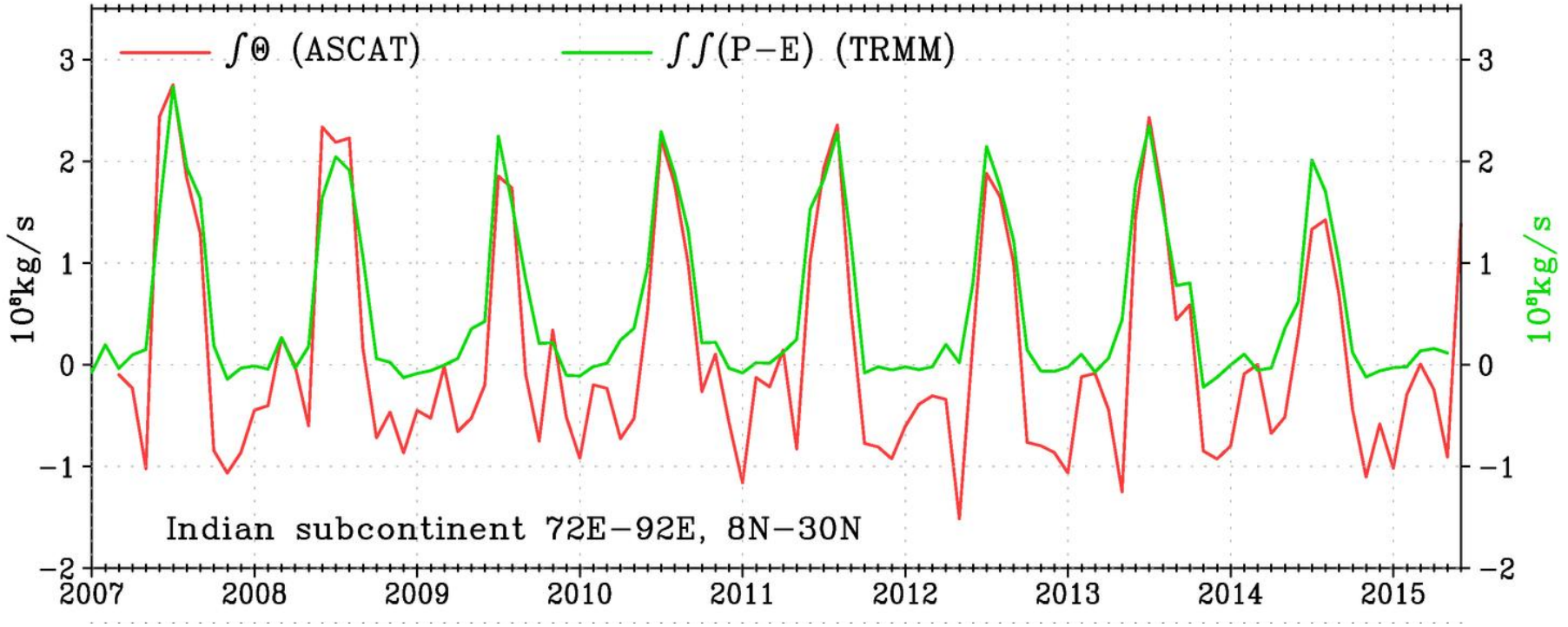





∫Θ (ASCAT)
∫∫(P−E) (TRMM)
Indian subcontinent 72E−92E, 8N−30N
10³kg/s
∫∫∂M/∂t (GRACE)
∫∫(P−E)−∫R (TRMM/altimeter)
Indian subcontinent 72E−92E, 8N−30N
10³kg/s
2007
2008
2009
2010
2011
2012
2013
2014
2015


River discharge at Irrawaddy (10⁶ m³/s)
Clim. (Dai & Trenberth)
Altimeter (Papa)
PU (Sheffield)
0.08
0.06
0.04
0.02
0
JAN
2011
JUL
JAN
2012
JUL
JAN
2013
JUL
JAN
2014
JUL


River discharge at Irrawaddy (10⁶ m³/s)
Clim. (Dai & Trenberth)
Altimeter (Papa)
PU (Sheffield)
0.08
0.06
0.04
0.02
0
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014


∫Θ (ASCAT)
∫∫(P−E) (TRMM)
Indian subcontinent 72E−92E, 8N−30N
10⁹kg/s
10⁹kg/s
3
2
1
0
−1
−2
2007
2008
2009
2010
2011
2012
2013
2014
2015