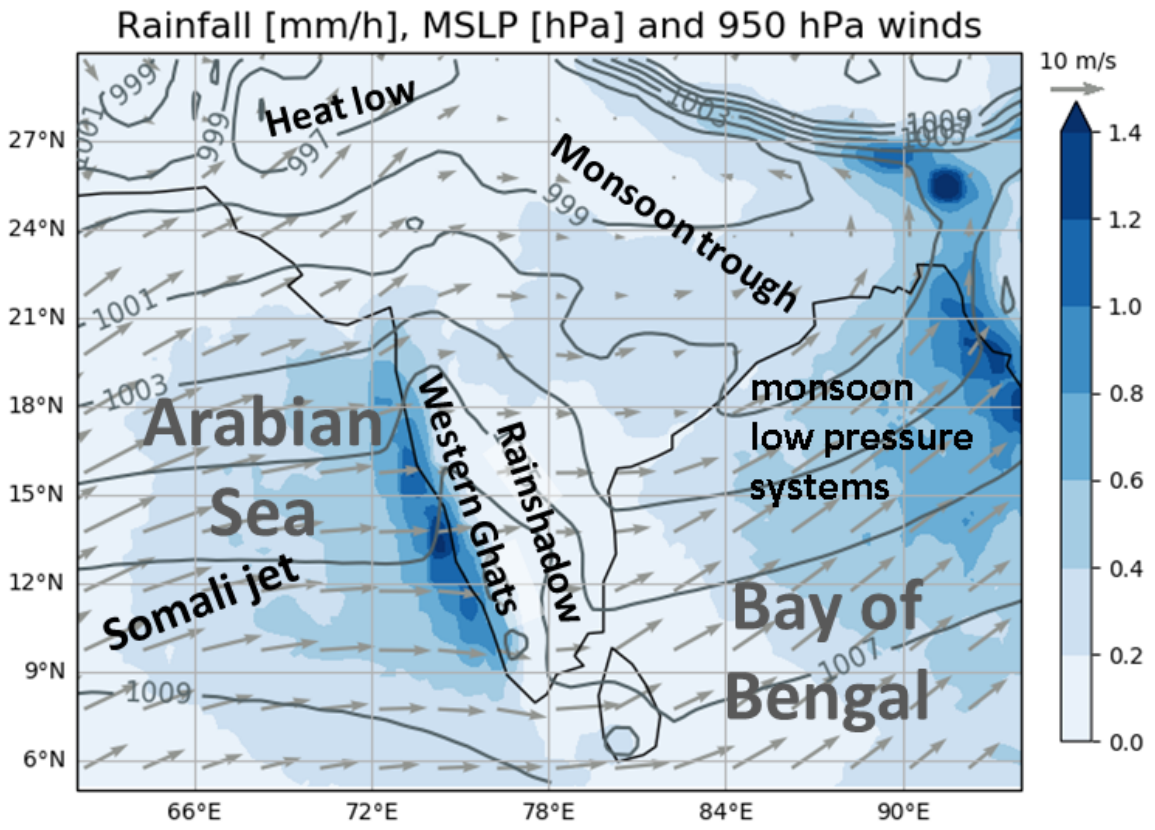
New INCOMPASS observations of the monsoon over southern India

with Doug Parker, Andrew Turner, Arathy Menon, Bob Houze, GS Bhat, G Mrudula, and many others

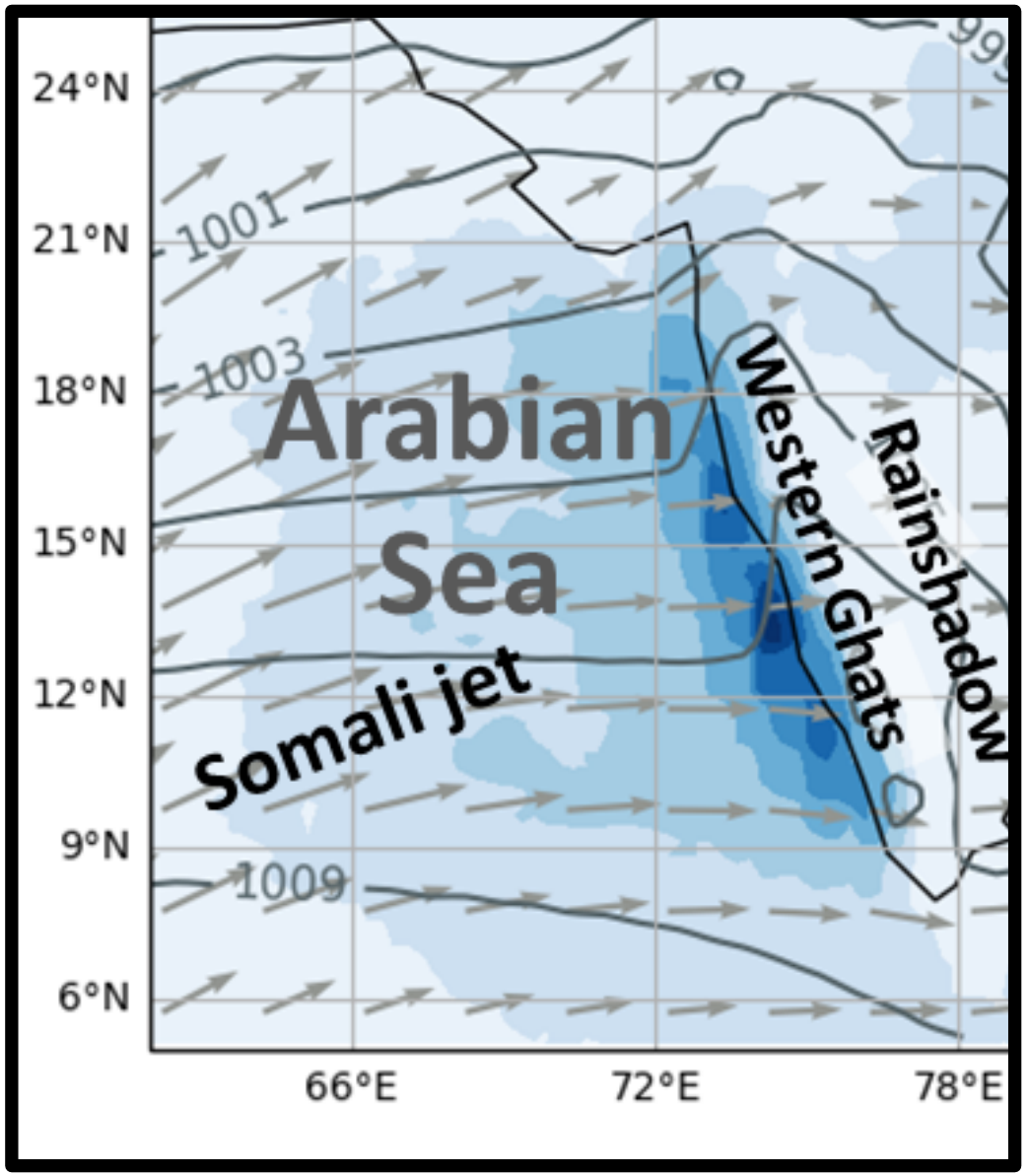
The spatial distribution of monsoon rainfall is strongly associated with orography

- Rainiest areas are where moist flow over oceans encounters mountains: the Meghalaya Plateau and upstream of Western Ghats and mountain ranges on Myanmar coast.
- In South India, the east coast is in the rain shadow and has a different peak rainfall season.



Research Questions

- What processes are associated with rainfall offshore?
- What is the boundary layer structure of the onshore flow?
- What produces rainfall over the tops of the Western Ghats and the rain shadow?



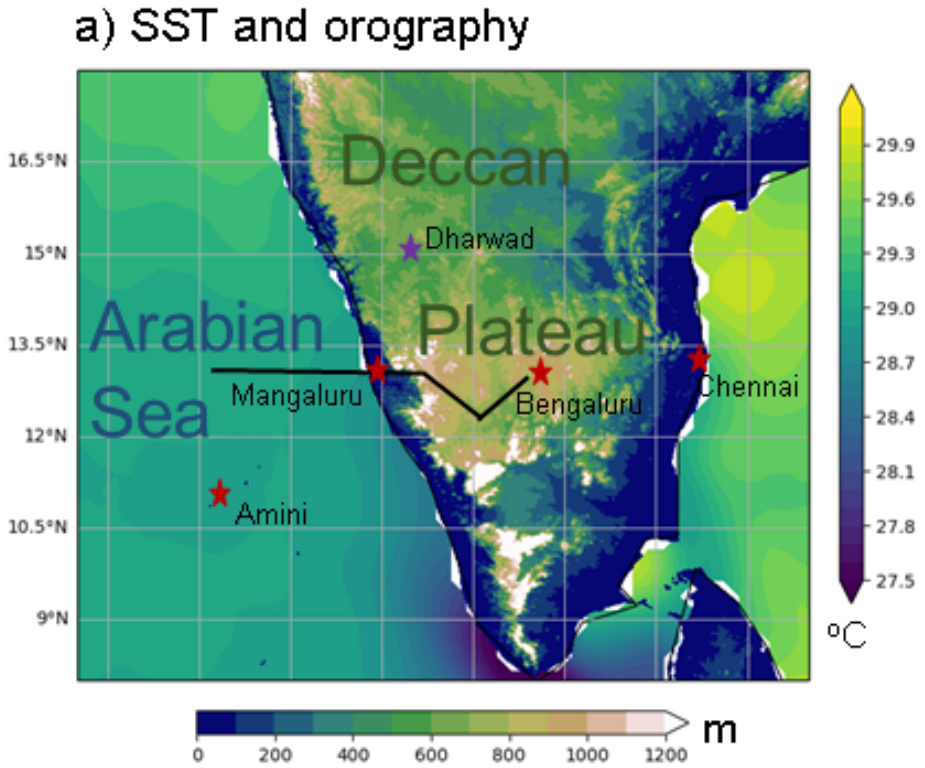
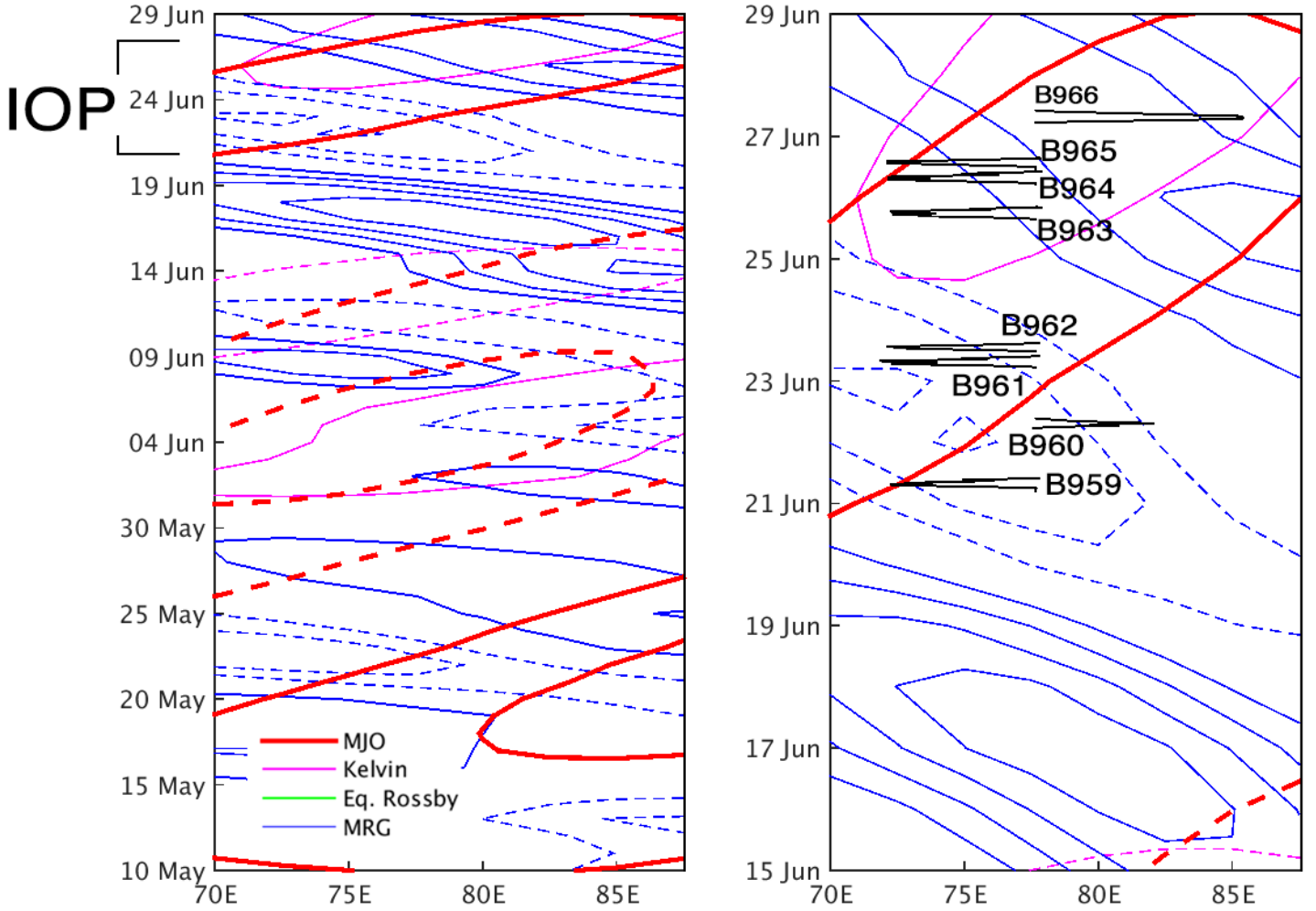


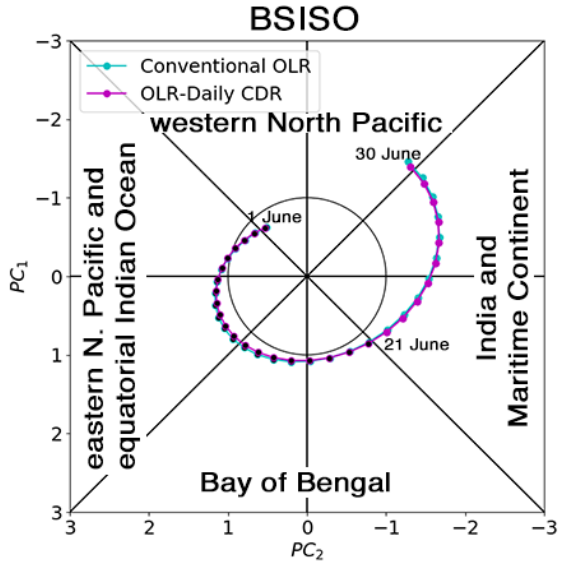
Photo by Adrian Pingstone

INCOMPASS South India IOP, June 2016

- Six flights over Western Ghats and eastern Arabian Sea
- Surveyed diurnal cycle and synoptic evolution over ten day period
- In situ aircraft data supplemented with radiosondes, satellite and reanalysis for context

The IOP was characterised by the passage of an active phase of the MJO/BSISO



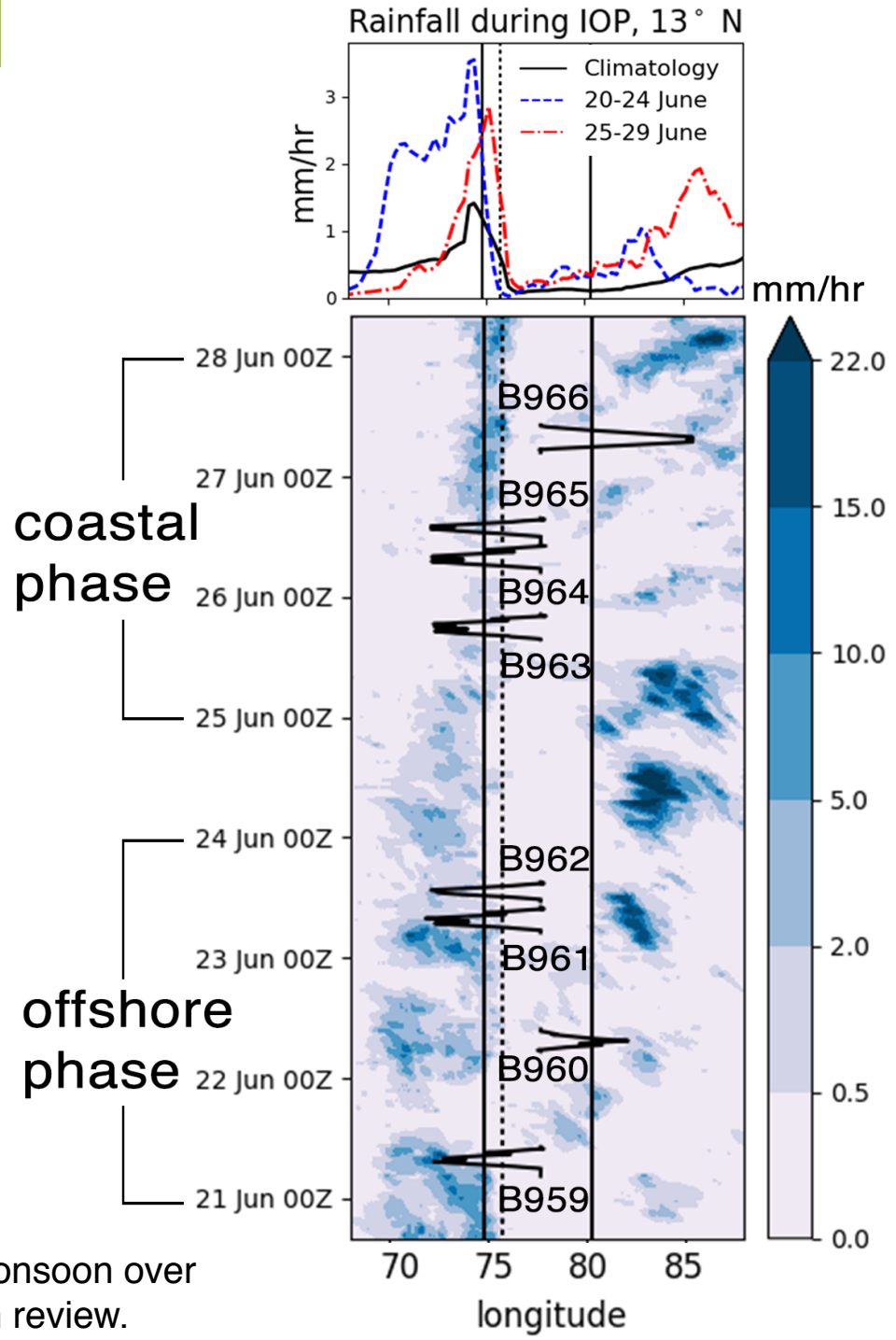


Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Using methods of Roundy et al 2012 and Kikuchi et al 2012

Two distinctive rainfall regimes associated with large scale mode

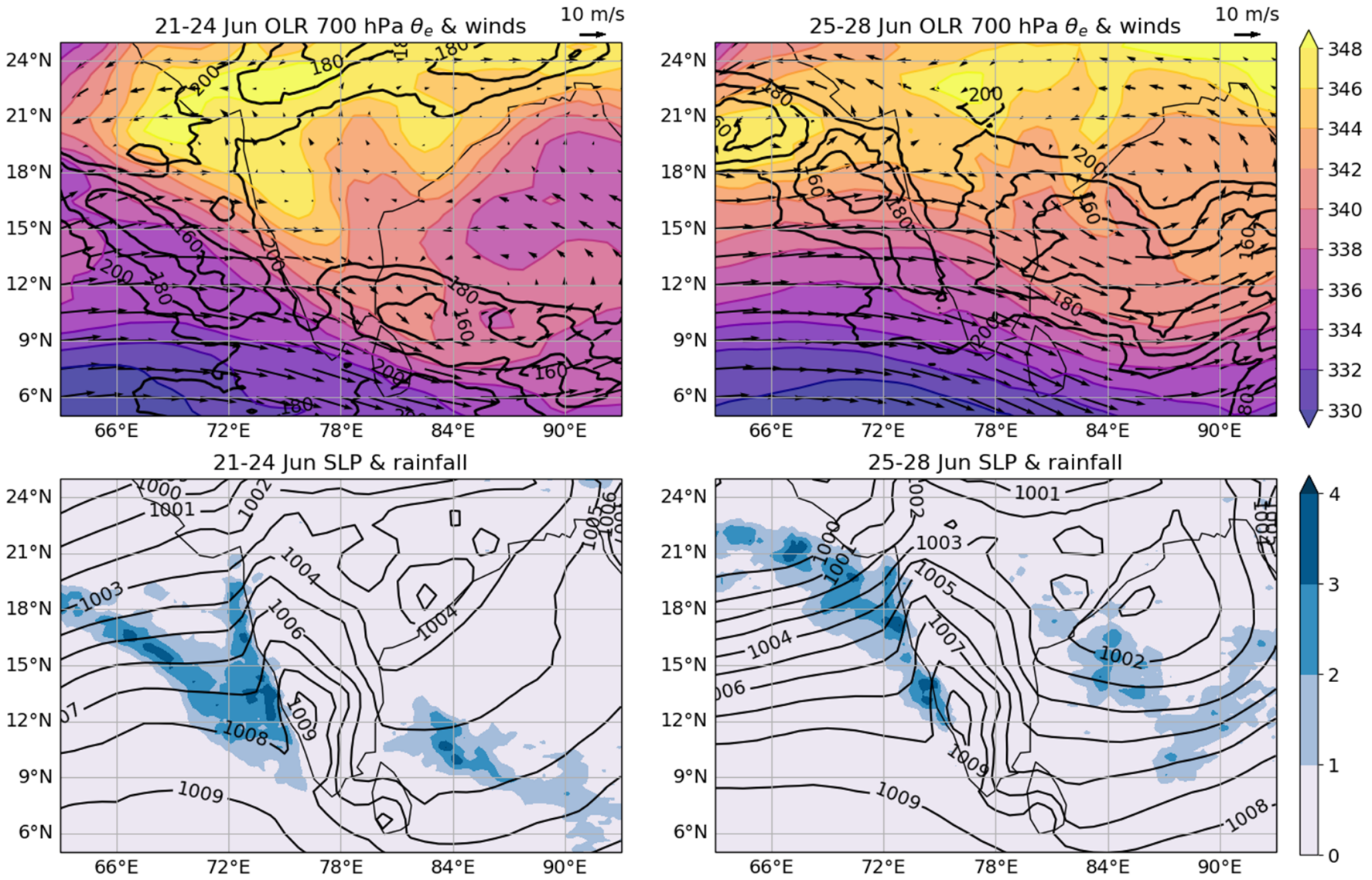
- **Offshore phase**
  - First half of IOP
  - Heavy rainfall over eastern Arabian Sea
  - Suppressed rainfall over coast and mountains
- **Coastal phase**
  - Second half of IOP
  - Intermittent rainfall over Arabian Sea
  - Heavy rainfall over coast and mountains



Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

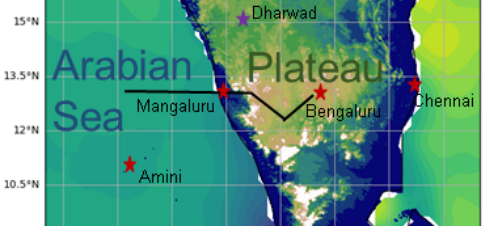
Offshore phase mean

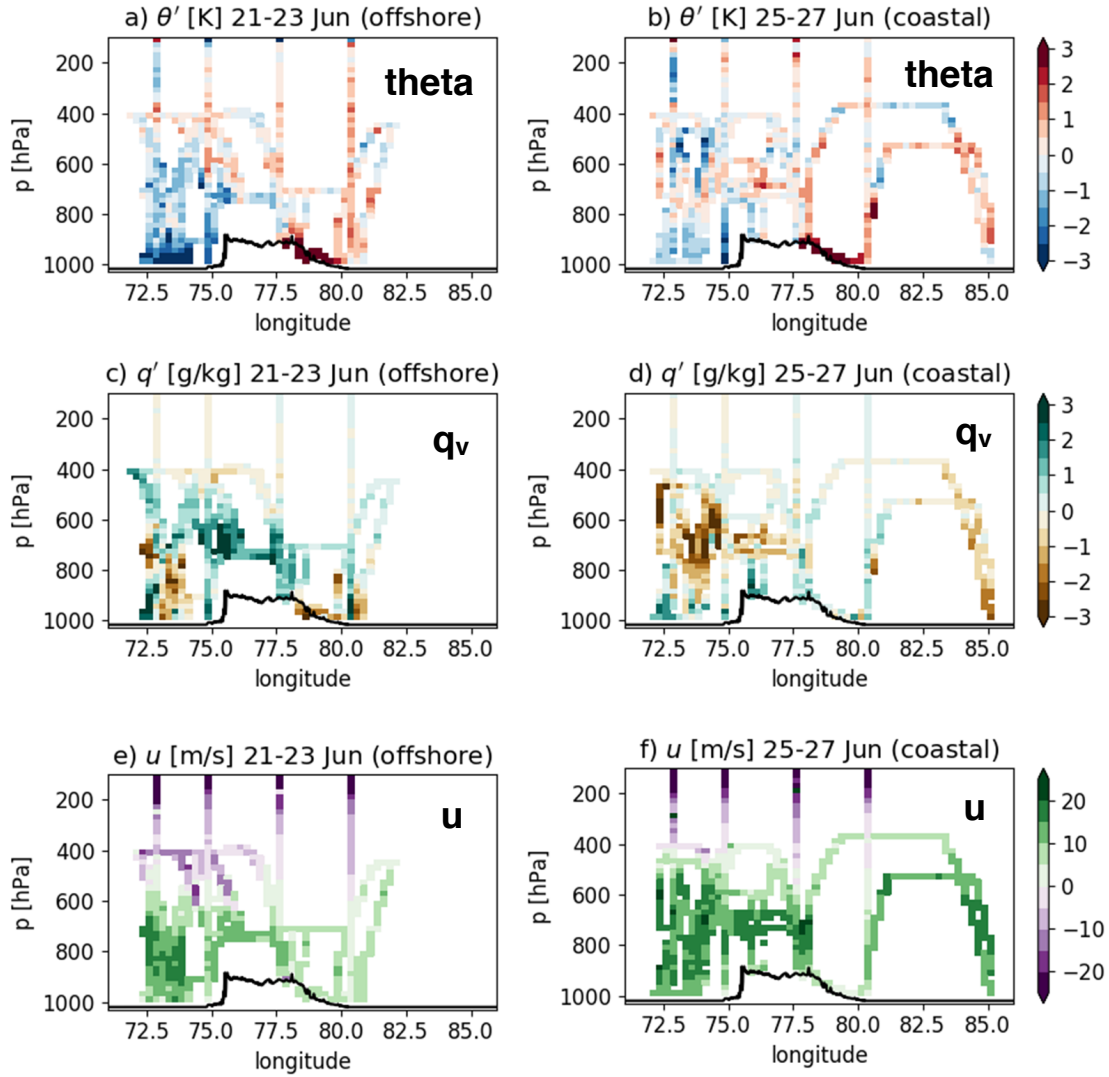
Coastal phase mean



Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

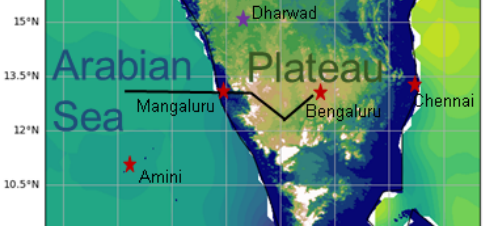
Combined aircraft and radiosonde observations averaged over offshore and coastal phases



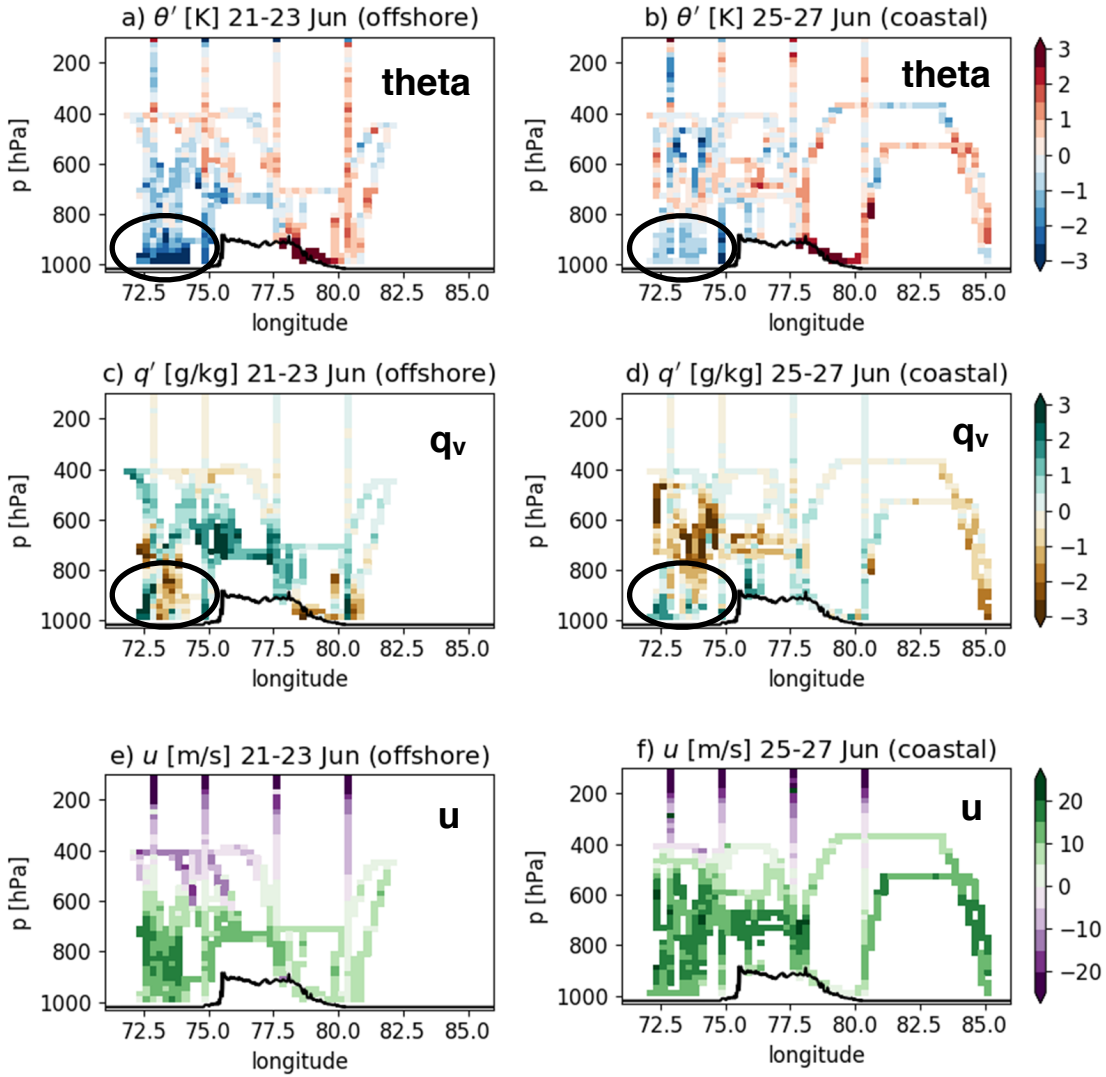


Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoo
southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Combined aircraft and radiosonde observations averaged over offshore and coastal phases

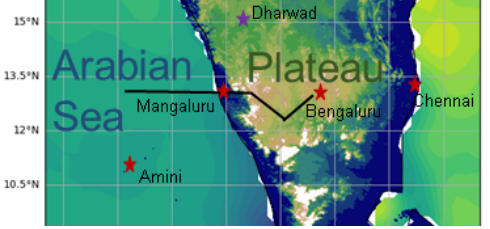


- **Offshore phase**
  - Cooler, dryer boundary layer over Arabian Sea
- **Coastal phase**
  - Warmer, moister boundary layer over Arabian Sea

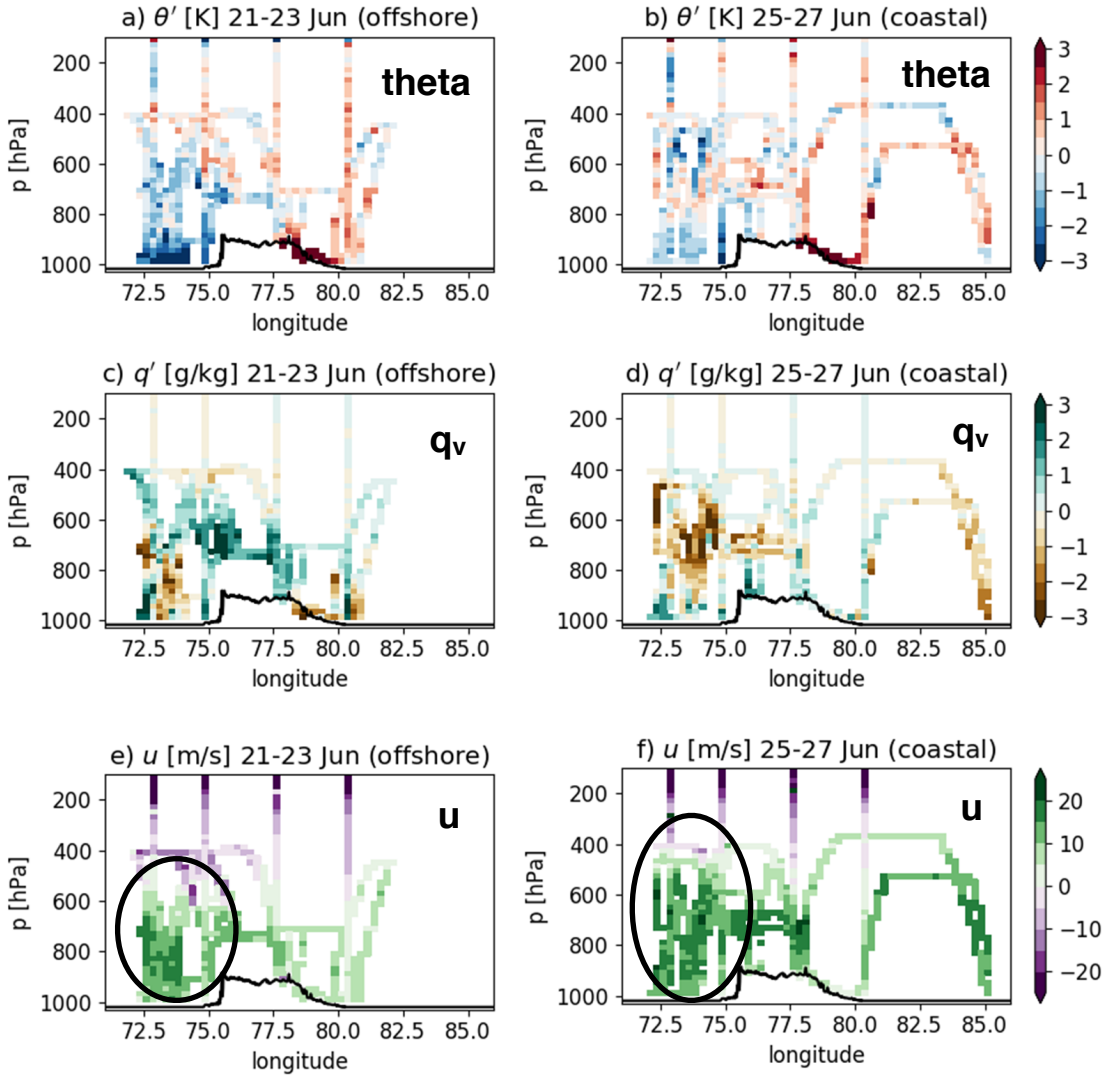


Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoo
southern India: New observations from the INCOMPASS IOP. *QJRMS*, in revie

Combined aircraft and radiosonde observations averaged over offshore and coastal phases

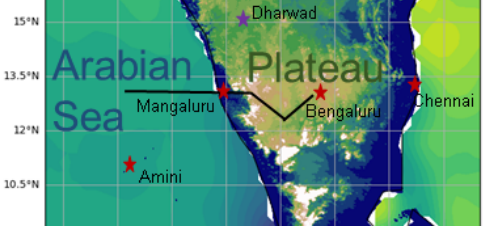


- **Offshore phase**
  - Cooler, dryer boundary layer over Arabian Sea
  - Weak onshore flow, low critical layer
- **Coastal phase**
  - Warmer, moister boundary layer over Arabian Sea
  - Stronger onshore flow, westerlies up to about 400 hPa

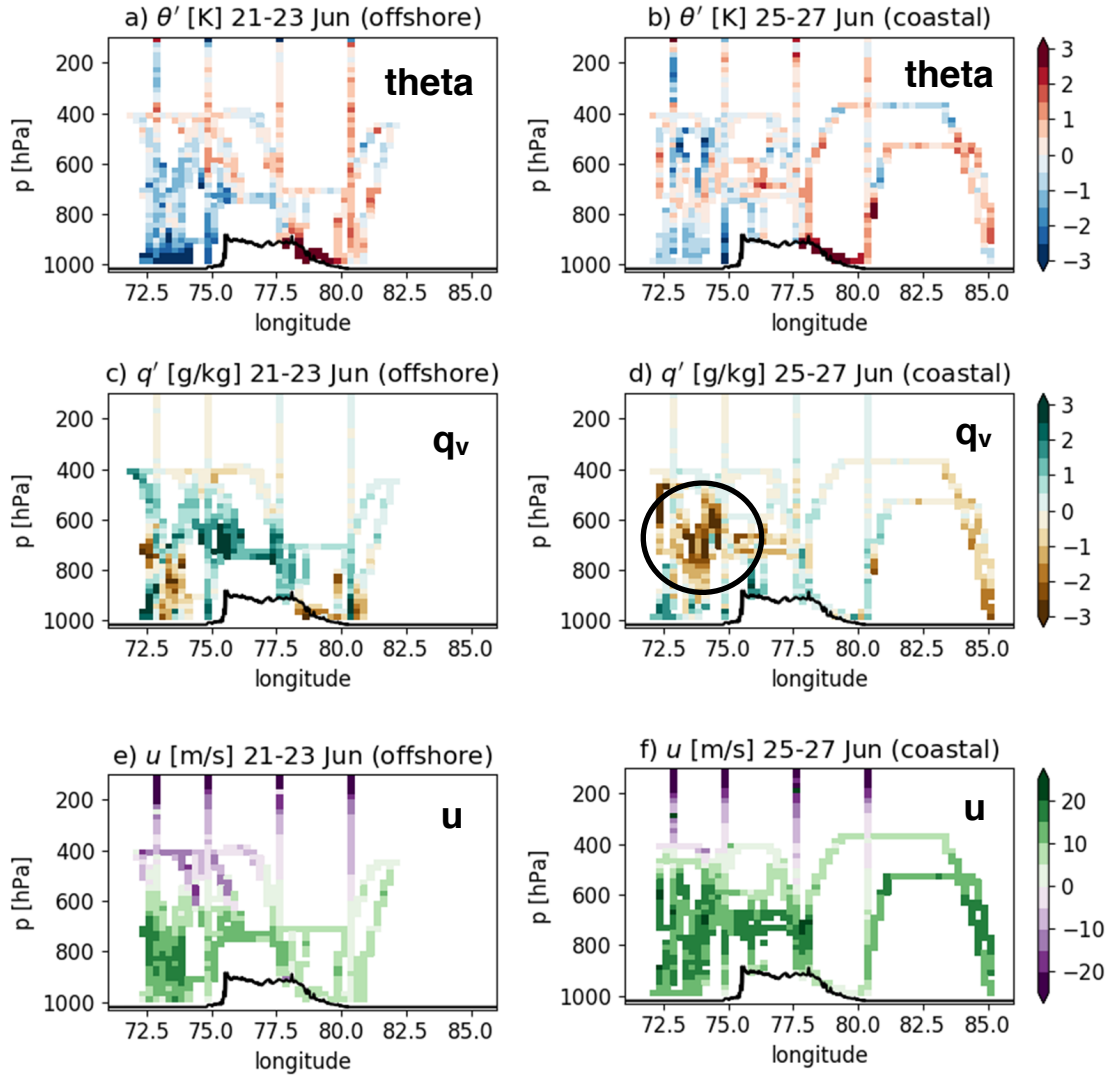


Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoo
southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Combined aircraft and radiosonde observations averaged over offshore and coastal phases



- **Offshore phase**
  - Cooler, dryer boundary layer over Arabian Sea
  - Weak onshore flow, low critical layer
- **Coastal phase**
  - Warmer, moister boundary layer over Arabian Sea
  - Stronger onshore flow, westerlies up to about 400 hPa
  - Mid-level dry layer from western Arabian Sea



Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoo
southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Controls on offshore rainfall

Flight number	phase	Time of day	Mean rainfall (mm/h)	SST (°C)	Fr	Amini CAPE	Mangl. CAPE	Mid-trop q (g/kg)
B959	Offshore	Day	2.3	28.58	0.6	889.0	156.7	6.5
B961	Offshore	Day	1.1	28.78	1.3	510.9	65.5	6.7
B962	Offshore	Evening	1.3	28.78	0.9	NA	340.6	6.3
B963	Coastal	Night	0.2	28.62	0.9	NA	175.8	5.1
B964	Coastal	Day	0.0	28.55	1.1	1370.0	715.0	3.3
B965	Coastal	Evening	0.8	28.55	1.0	NA	2158.6	4.5

Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Slightly cooler SST during coastal phase

Flight number	phase	Time of day	Mean rainfall (mm/h)	SST (°C)	Fr	Amini CAPE	Mangl. CAPE	Mid-trop q (g/kg)
B959	Offshore	Day	2.3	28.58	0.6	889.0	156.7	6.5
B961	Offshore	Day	1.1	28.78	1.3	510.9	65.5	6.7
B962	Offshore	Evening	1.3	28.78	0.9	NA	340.6	6.3
B963	Coastal	Night	0.2	28.62	0.9	NA	175.8	5.1
B964	Coastal	Day	0.0	28.55	1.1	1370.0	715.0	3.3
B965	Coastal	Evening	0.8	28.55	1.0	NA	2158.6	4.5

Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Flow is mostly unblocked in both phases

Flight number	phase	Time of day	Mean rainfall (mm/h)	SST (°C)	Fr	Amini CAPE	Mangl. CAPE	Mid-trop q (g/kg)
B959	Offshore	Day	2.3	28.58	0.6	889.0	156.7	6.5
B961	Offshore	Day	1.1	28.78	1.3	510.9	65.5	6.7
B962	Offshore	Evening	1.3	28.78	0.9	NA	340.6	6.3
B963	Coastal	Night	0.2	28.62	0.9	NA	175.8	5.1
B964	Coastal	Day	0.0	28.55	1.1	1370.0	715.0	3.3
B965	Coastal	Evening	0.8	28.55	1.0	NA	2158.6	4.5

Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

CAPE is anti correlated with offshore rainfall due to buildup of BL humidity

Flight number	phase	Time of day	Mean rainfall (mm/h)	SST (°C)	Fr	Amini CAPE	Mangl. CAPE	Mid-trop q (g/kg)
B959	Offshore	Day	2.3	28.58	0.6	889.0	156.7	6.5
B961	Offshore	Day	1.1	28.78	1.3	510.9	65.5	6.7
B962	Offshore	Evening	1.3	28.78	0.9	NA	340.6	6.3
B963	Coastal	Night	0.2	28.62	0.9	NA	175.8	5.1
B964	Coastal	Day	0.0	28.55	1.1	1370.0	715.0	3.3
B965	Coastal	Evening	0.8	28.55	1.0	NA	2158.6	4.5

Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

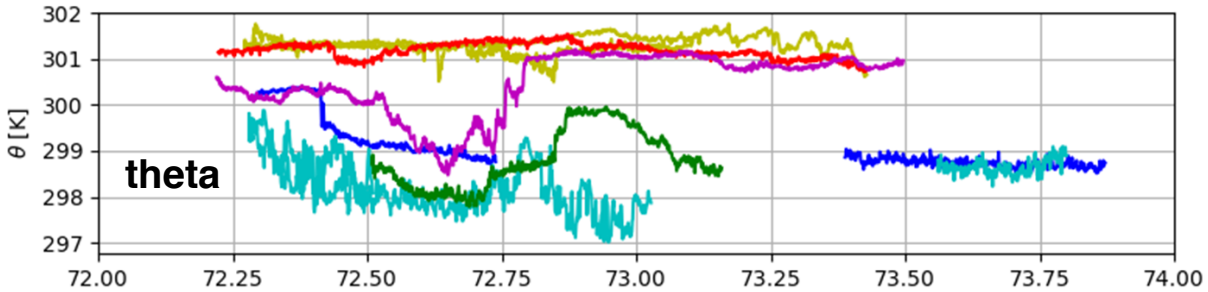
Mid-tropospheric drying associated with reduced rainfall offshore

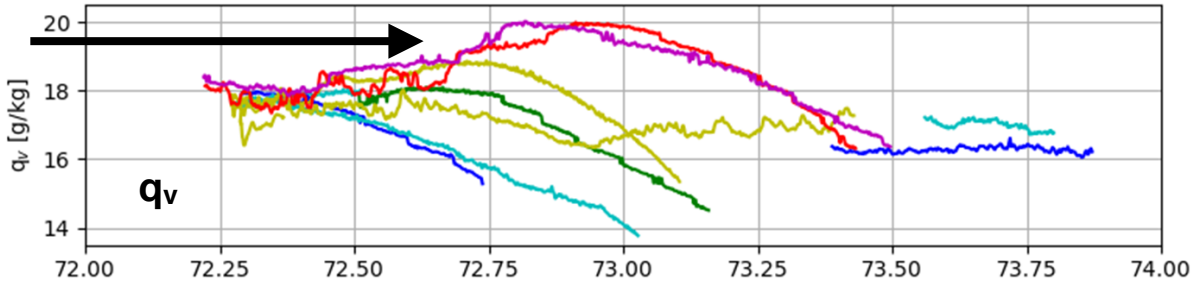
Flight number	phase	Time of day	Mean rainfall (mm/h)	SST (°C)	Fr	Amini CAPE	Mangl. CAPE	Mid-trop q (g/kg)
B959	Offshore	Day	2.3	28.58	0.6	889.0	156.7	6.5
B961	Offshore	Day	1.1	28.78	1.3	510.9	65.5	6.7
B962	Offshore	Evening	1.3	28.78	0.9	NA	340.6	6.3
B963	Coastal	Night	0.2	28.62	0.9	NA	175.8	5.1
B964	Coastal	Day	0.0	28.55	1.1	1370.0	715.0	3.3
B965	Coastal	Evening	0.8	28.55	1.0	NA	2158.6	4.5

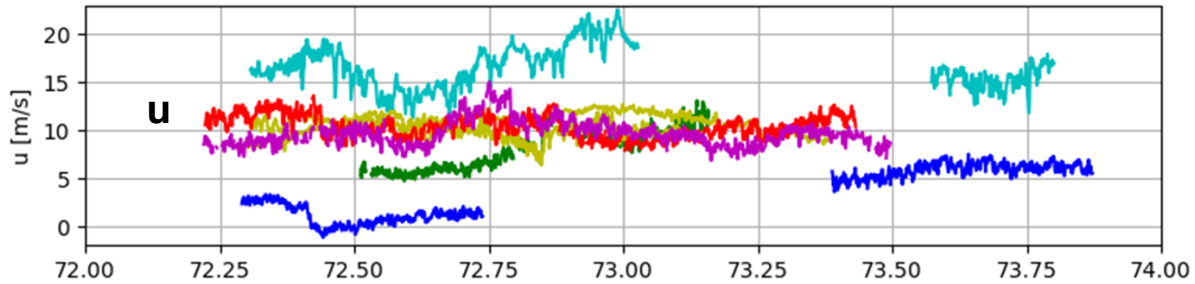
Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

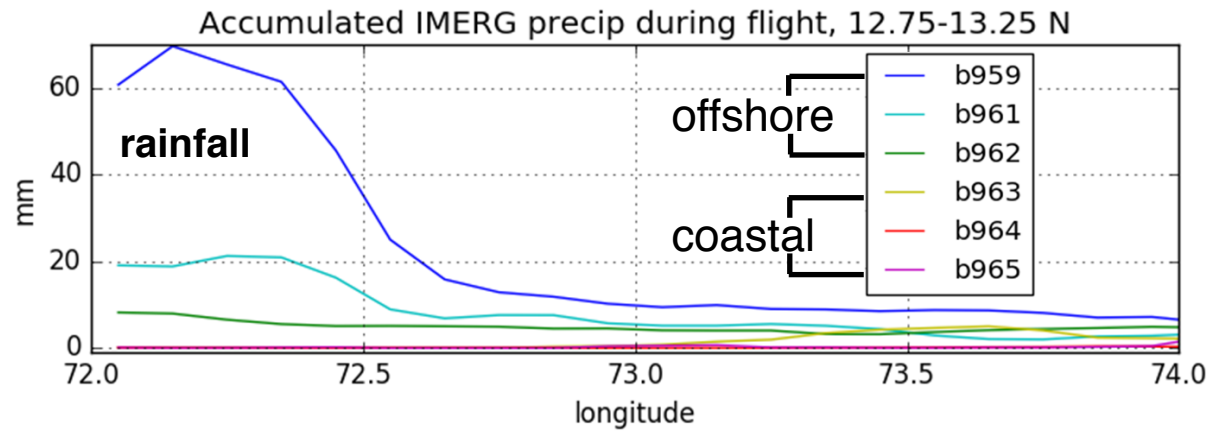
Data from low level runs (below 500 m)

Arabian Sea boundary layer: during the **coastal phase**, when convection was suppressed offshore, **boundary layer humidity built up to the highest levels** observed in the campaign.



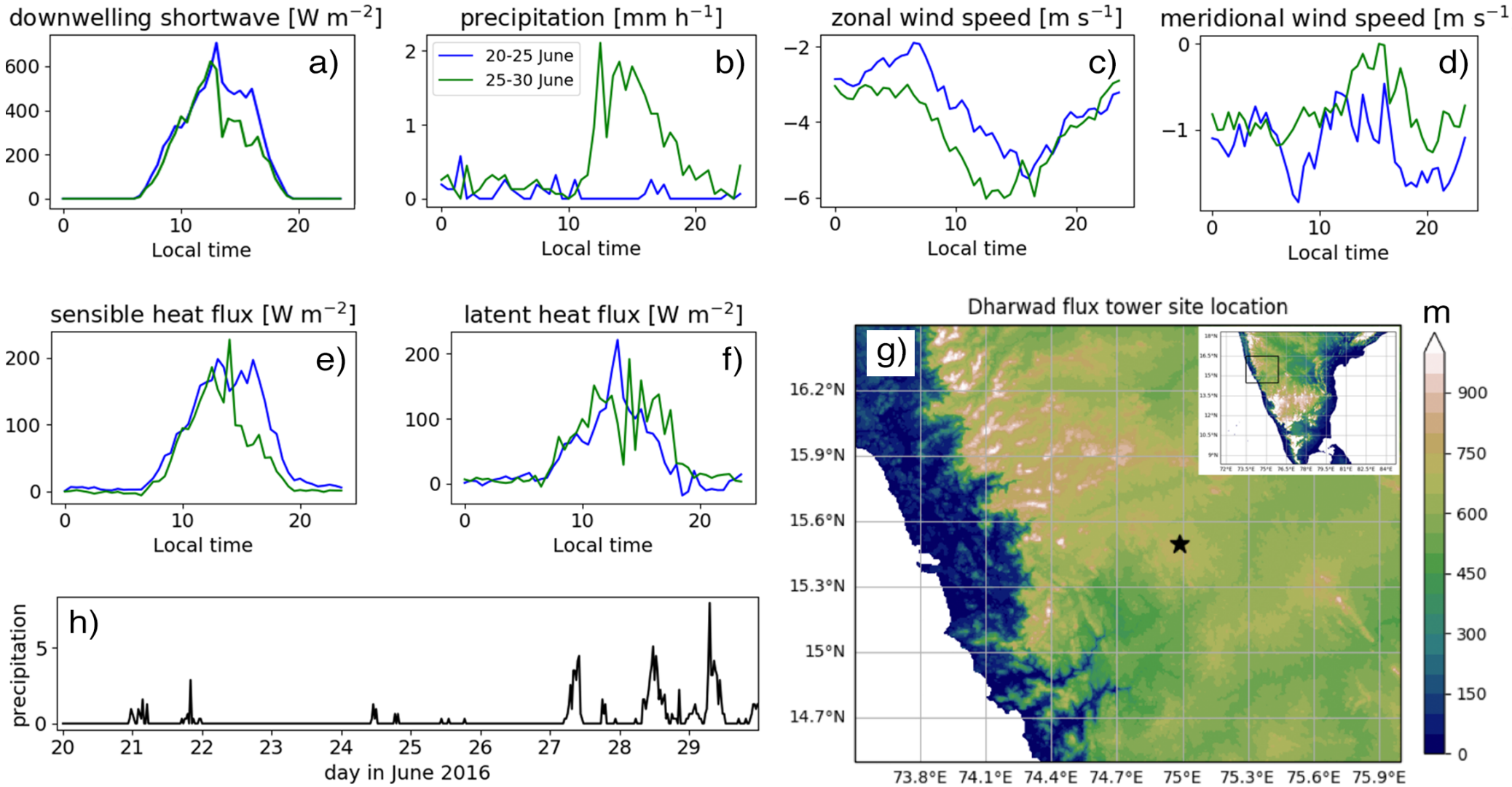






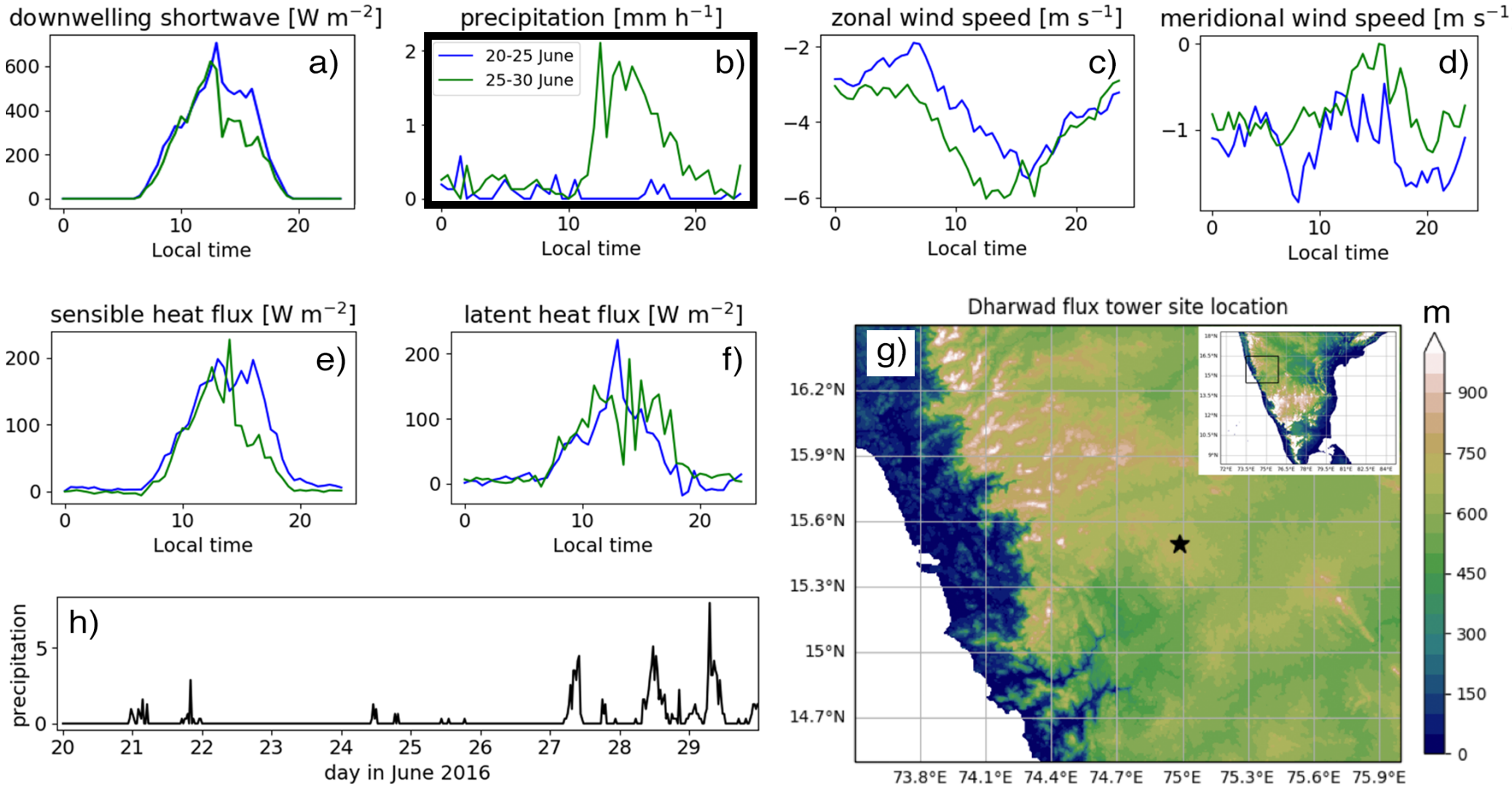
Fletcher et al, 2018: The dynamic and thermodyn
southern India: New observations from the INCOI

Observations in the Western Ghats



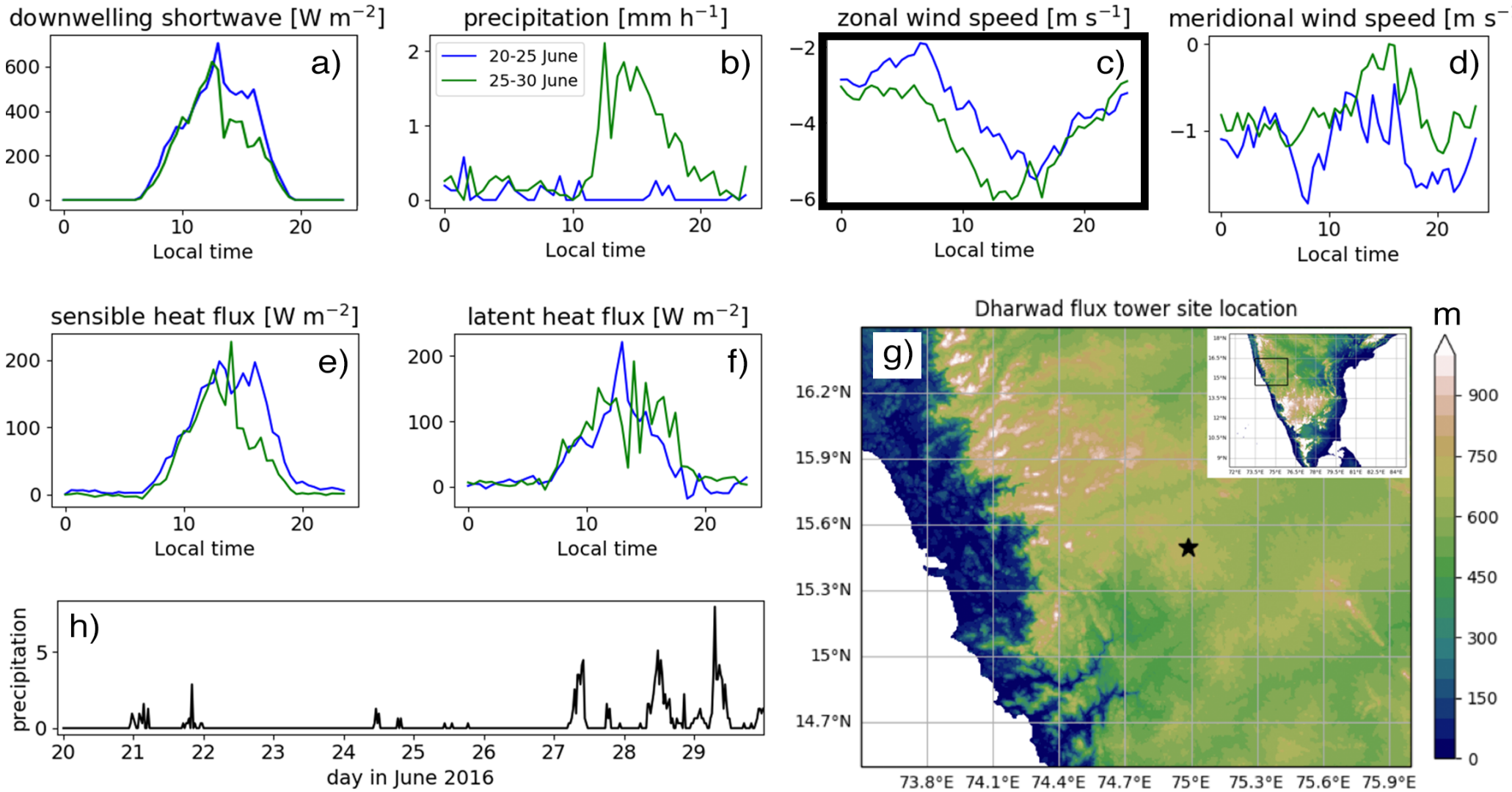
Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Afternoon rainfall during coastal phase



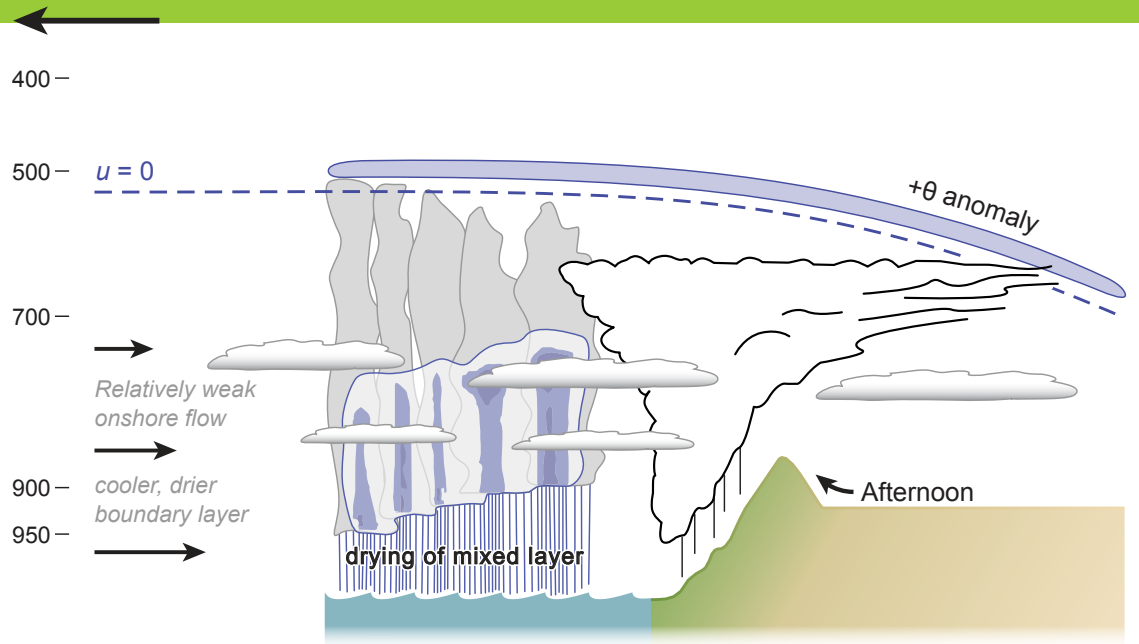
Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

Upslope easterlies stronger, earlier in coastal phase

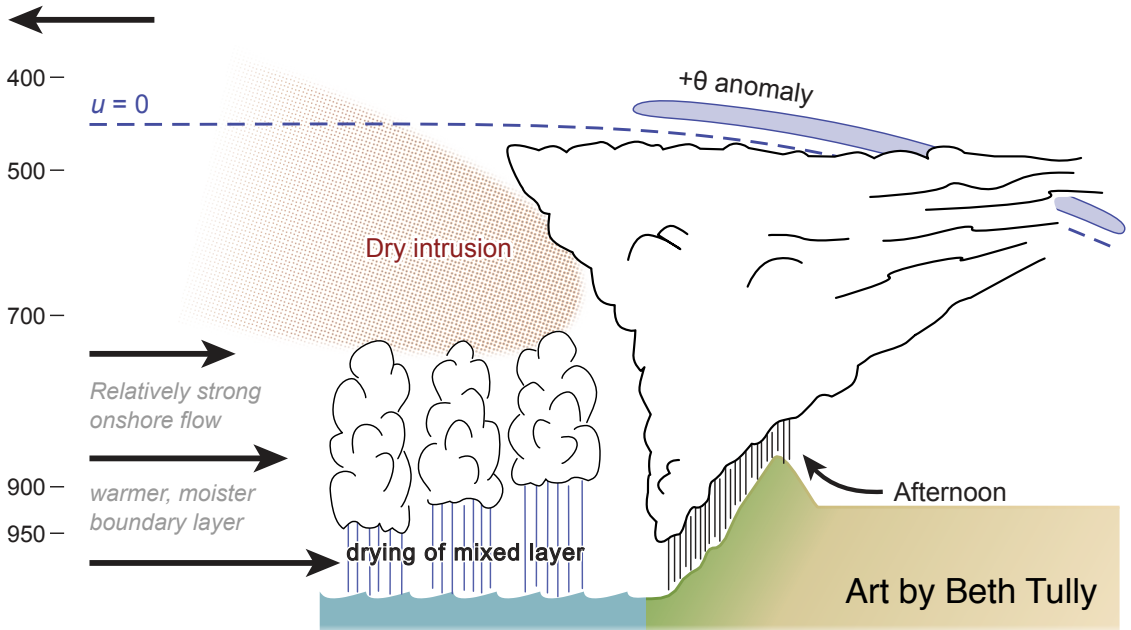


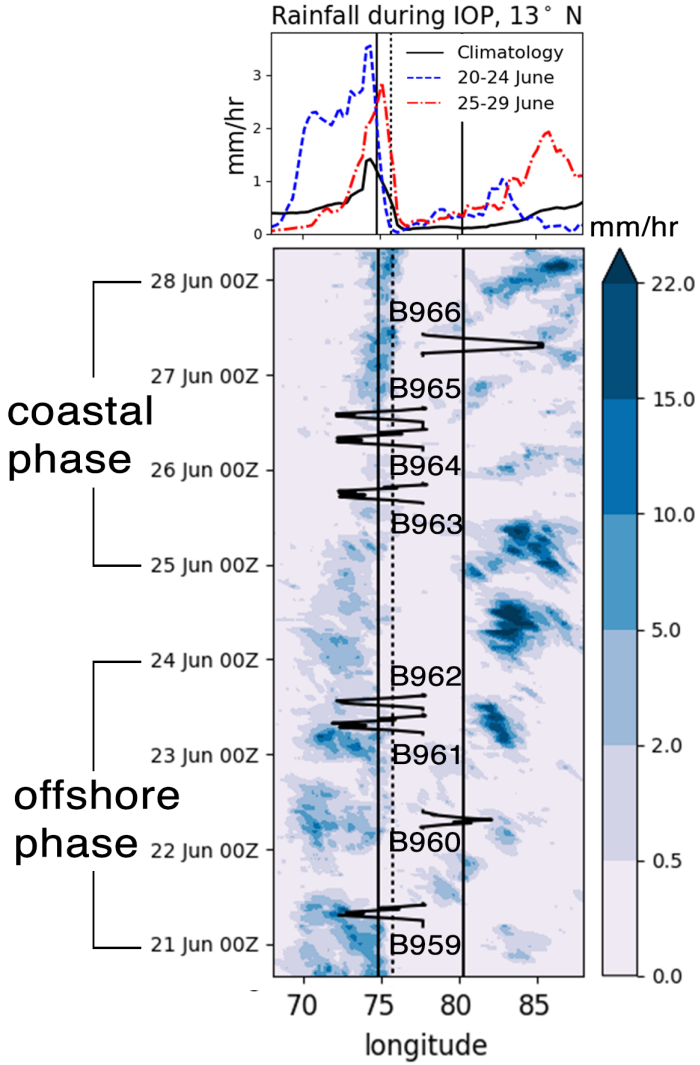
Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

(a) Offshore phase



(b) Coastal phase



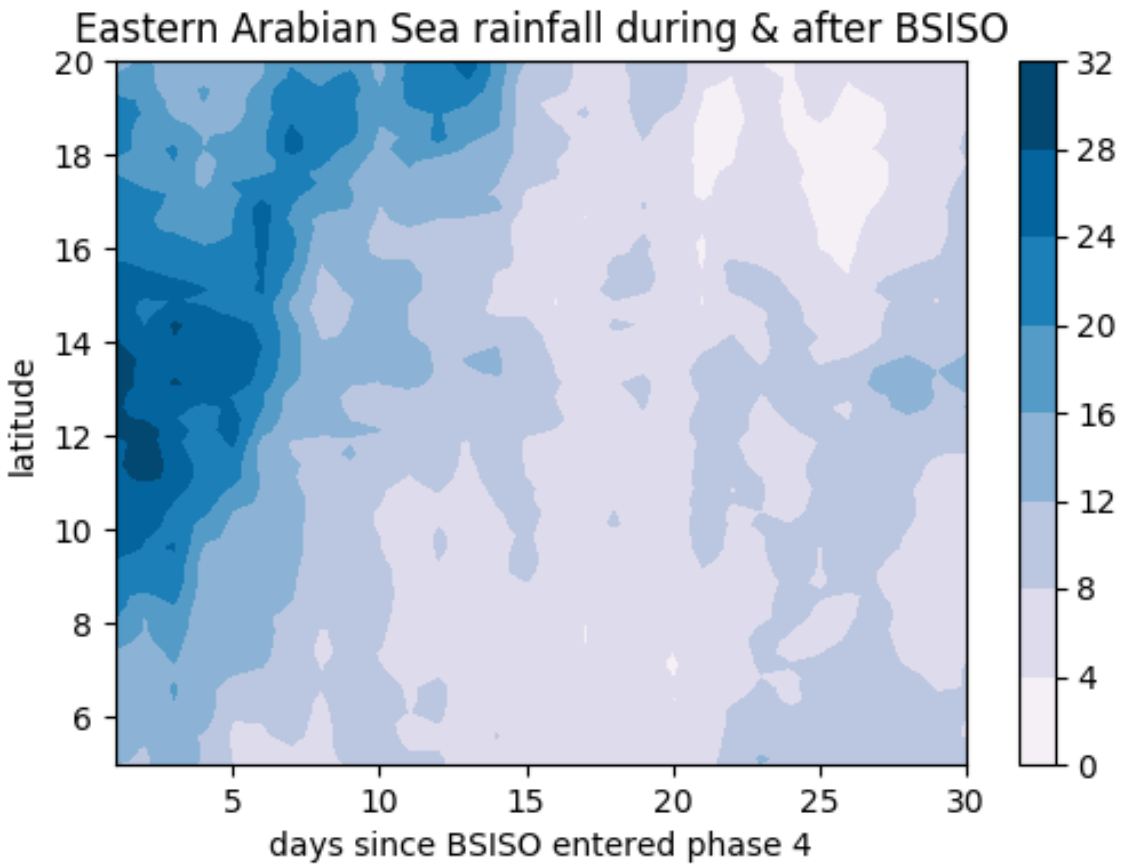


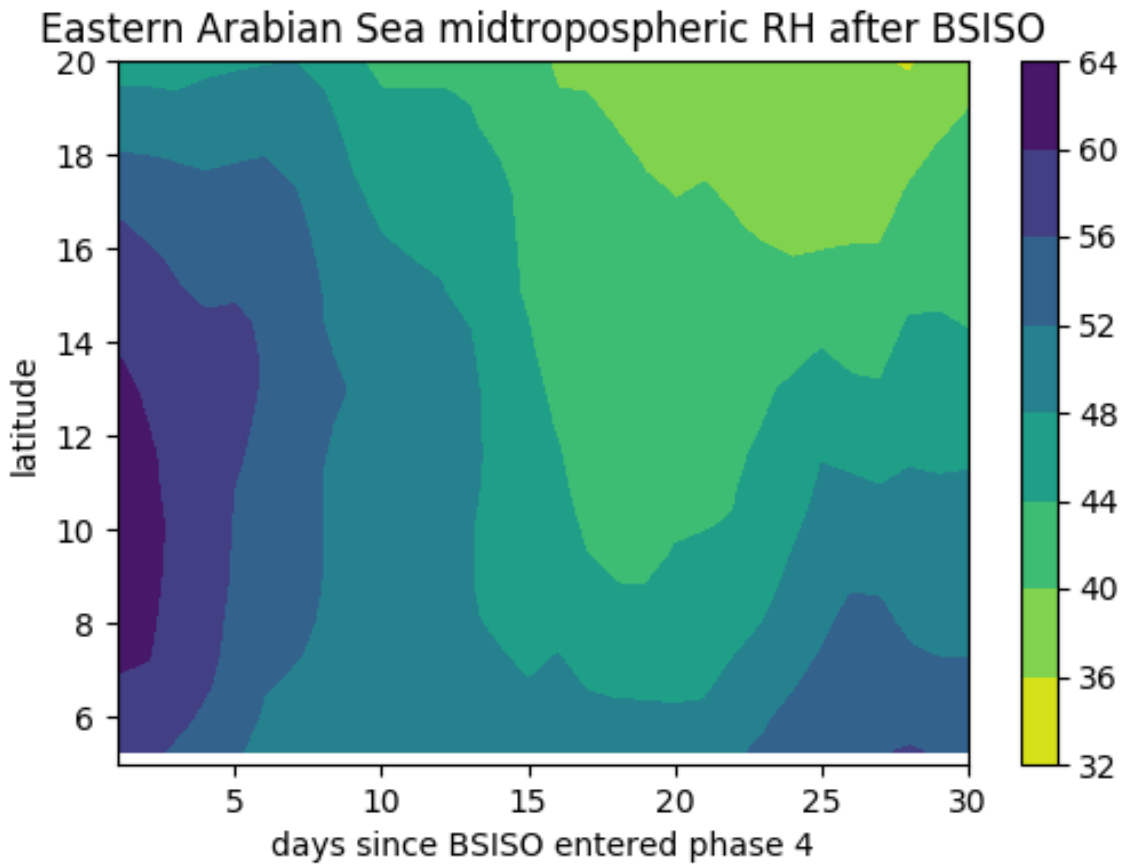
Hypotheses to investigate further

- Local thermodynamic properties play a more important role in offshore rainfall than orographic blocking does.
- Mid-tropospheric dry intrusions are a major determinant of offshore rainfall and in the thermodynamics of the onshore flow.
- Upslope flow on the lee side of the Western Ghats occurs in the afternoon and can contribute to convective triggering on the mountain tops and rain shadow if other conditions permit.

Thank you

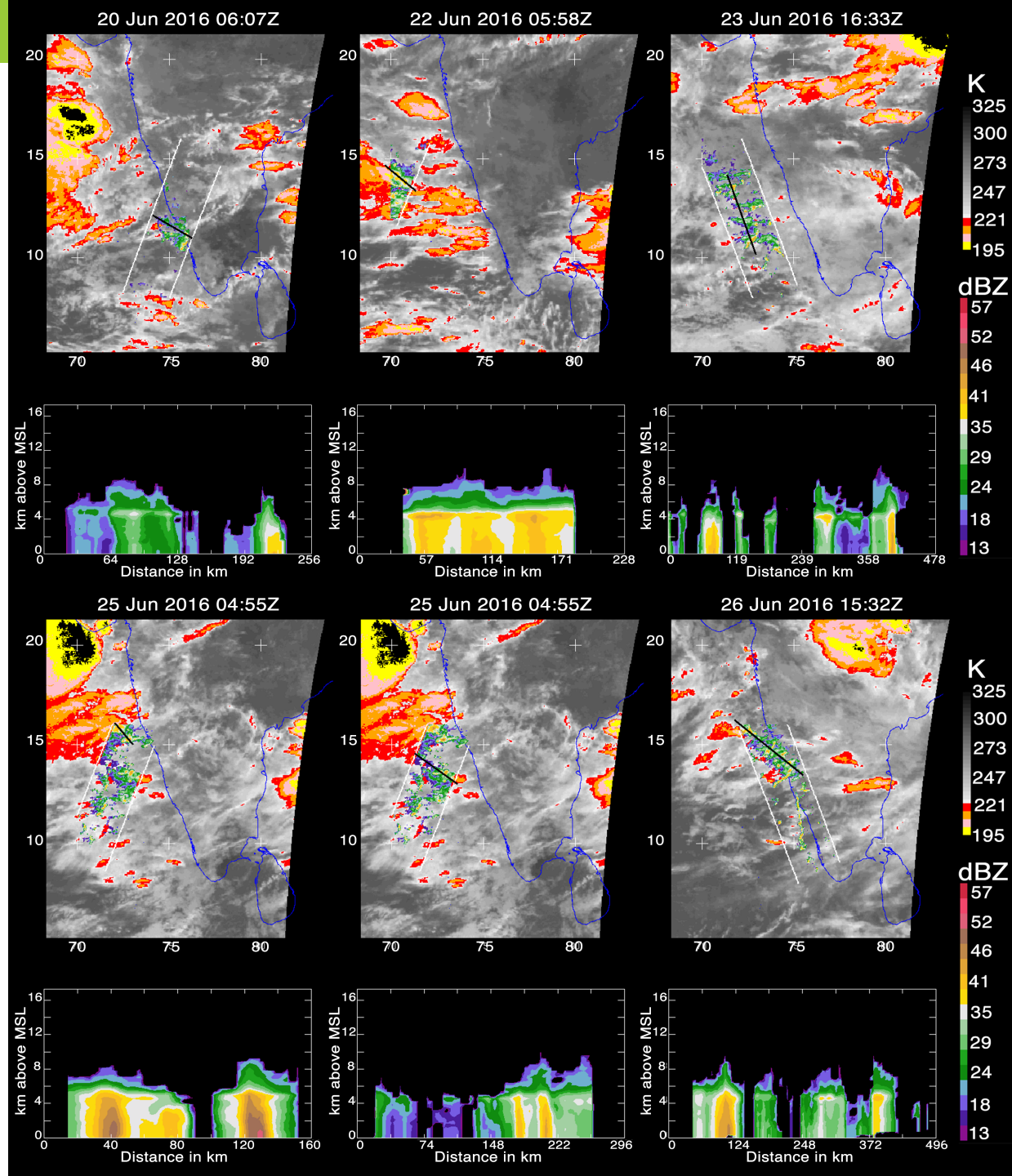
Are these precipitation responses over ocean and land generally seen with the passage of the BSISO?





Met7/GPM IR and reflectivity

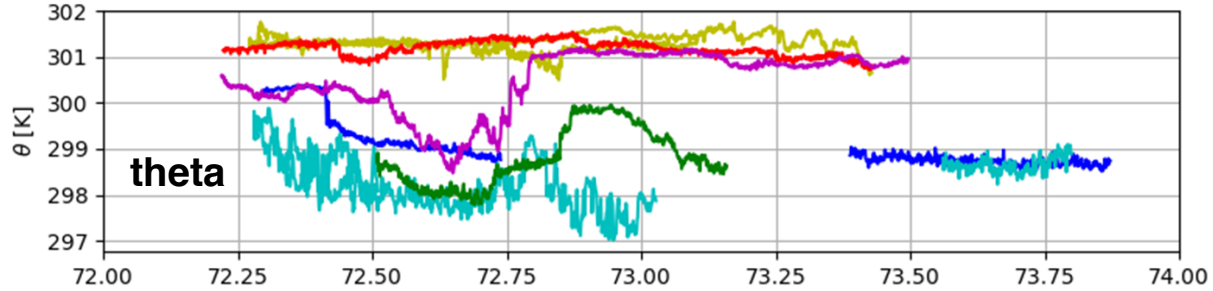
- Precipitation shifts from stratiform to convective over the course of the IOP
- Offshore rainfall in the evening is congestus-like.

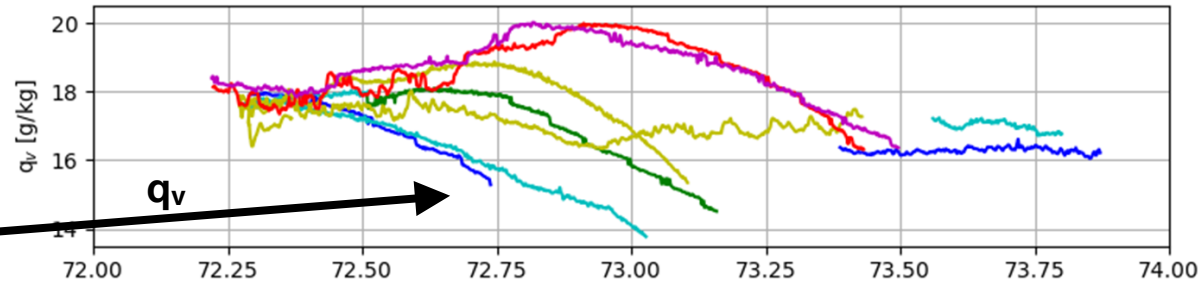


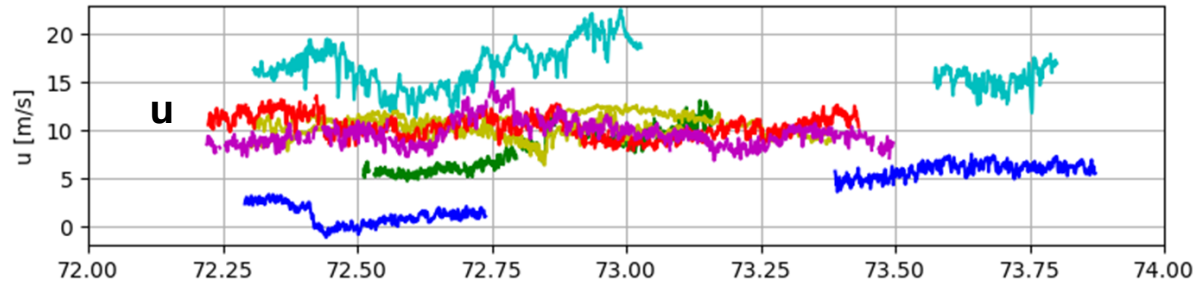
Fletcher et al, 2018: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *QJRMS*, in review.

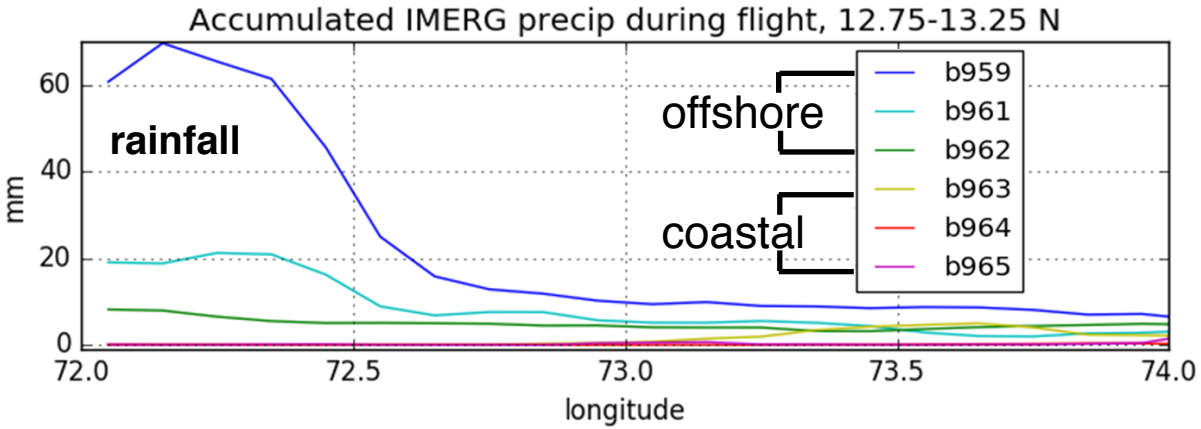
Data from low level runs (below 500 m)

- Arabian Sea boundary layer: low level drying observed in all flights as the onshore flow approached the coast.
- Boundary layer moisture budget analysis suggests this is due to entrainment of free tropospheric air/ downdrafts





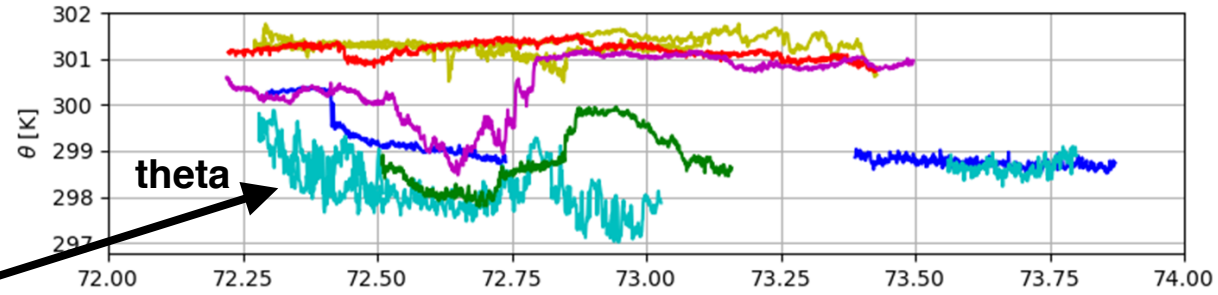


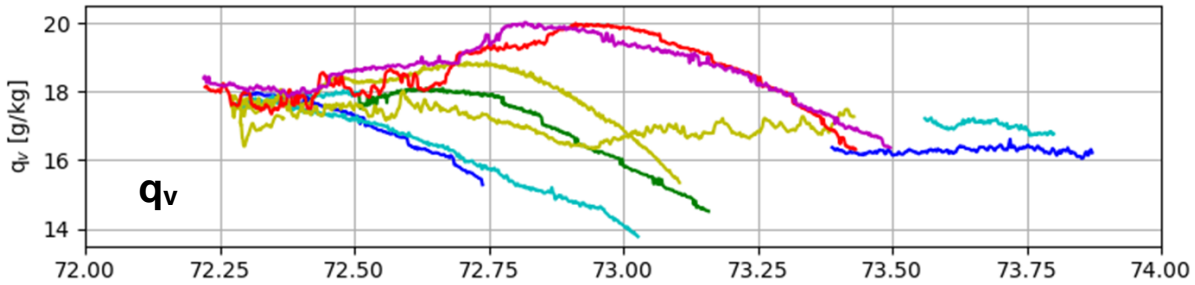


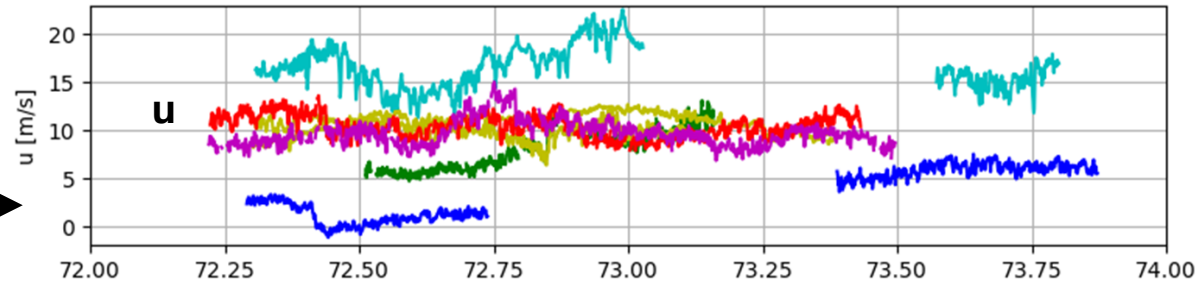
Fletcher et al, 2018: The dynamic and thermodyn
southern India: New observations from the INCOI

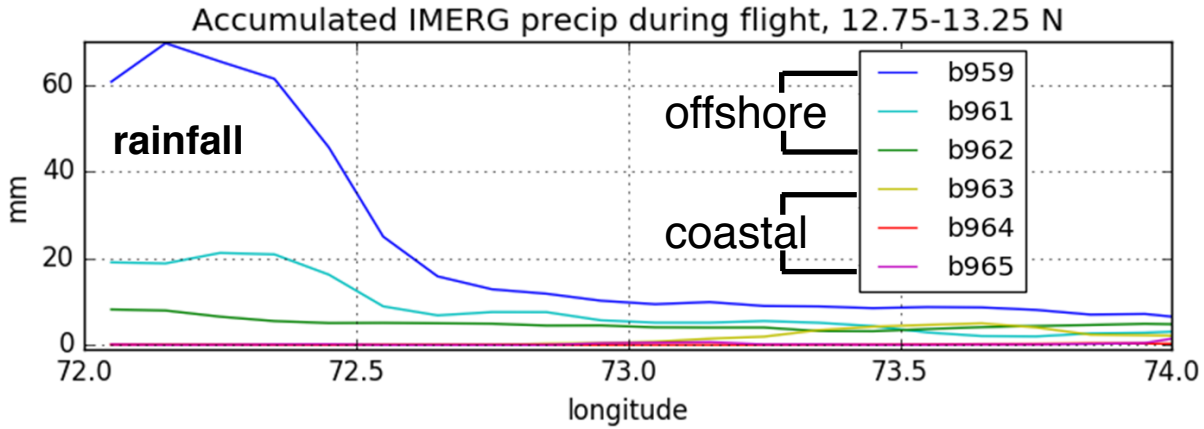
Data from low level runs (below 500 m)

There is considerable variability in temperature and winds, especially in the offshore phase when convection was active









Fletcher et al, 2018: The dynamic and thermodyn
southern India: New observations from the INCOI