Air-sea flux and SST variability associated with atmospheric rivers in the southeast Indian Ocean

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Abstract: A previous study demonstrated that atmospheric rivers (ARs) generate substantial air-sea fluxes in the northeast Pacific. Since the southeast Indian Ocean is one of the active regions of ARs, similar air-sea fluxes could be produced. However, the spatial pattern of sea surface temperature (SST) in the southeast Indian Ocean, especially along the west coast of Australia, is different from that in the northeast Pacific because of the poleward flowing Leeuwin Current, which may cause different air-sea fluxes. This study investigates AR-associated air-sea fluxes in the southeast Indian Ocean and their relation with SST variability based on the analysis of surface winds from Cross-Calibrated Multi-Platform wind vector analysis (CCMP) version 3 and surface fluxes from the Objectively Analyzed air-sea Fluxes (OAFlux) product. The large-scale spatial pattern of latent heat flux (evaporation) associated with ARs in the southeast Indian Ocean is similar to that in the northeast Pacific. A significant difference is however found near the coastal area where relatively warm SSTs are maintained in all seasons. While AR-induced latent heat flux is close to zero around the west coast of North America where the equatorward flowing coastal current and upwelling generate relatively cold SSTs, a significant latent heat flux induced by ARs is evident along the west coast of Australia due to the relatively warm surface waters. Temporal variations of coastal air-sea fluxes associated with landfalling ARs are investigated based on the composite analysis. While the moisture advection reduces the latent heat during landfalling, the reduction of air humidity with strong winds enhances large evaporative cooling (latent heat flux) after a few days of the landfalling. A significant SST cooling along the coast is found due to the enhanced latent heat flux.

Warm climatological SSTs near the west coast of Australia

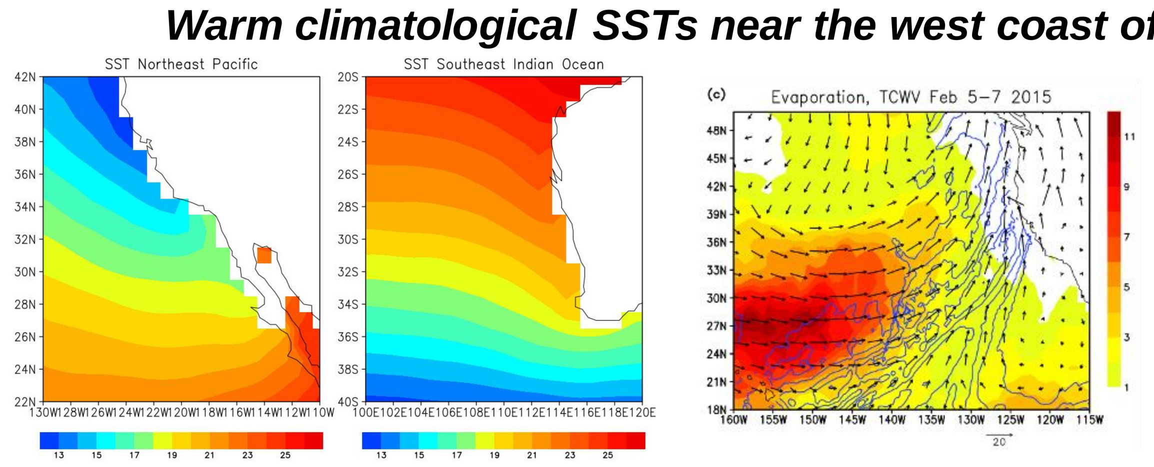


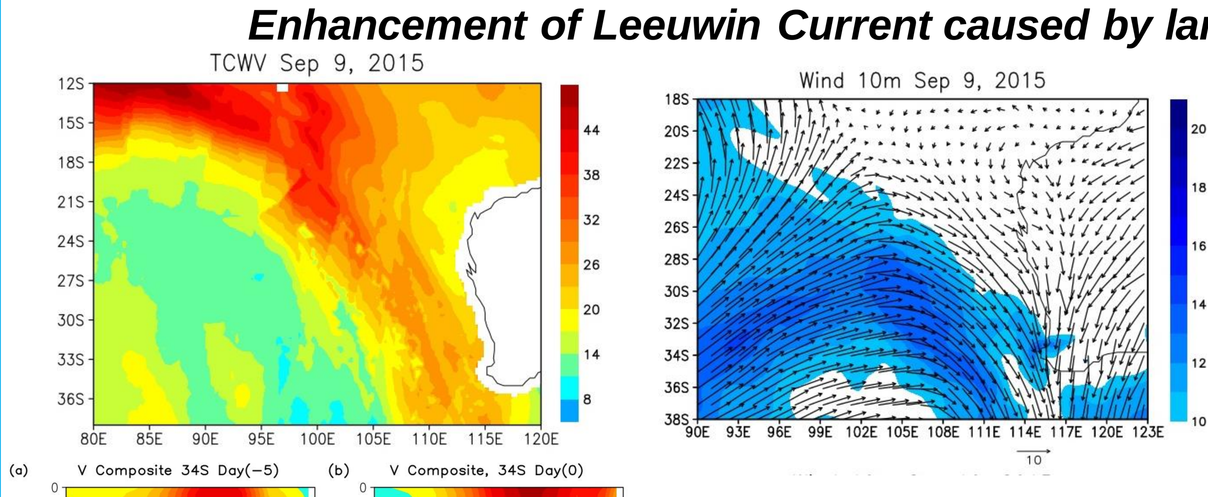
Figure 1. Left panels: Annual mean SST in the northeast Pacific (left panel) and the southeast Indian Ocean (right panel) derived from OAFlux. Right panel: AR-associated evaporation (mm/day: shading) on February 5–7, 2015, winds (m/s) at 10 m (arrows) on February 6, and total column integrated water vapor (contour) on February 6 in the northeast Pacific. Adapted from Shinoda et al. (2019).

Climatological SSTs along the west coast of Australia are 4-5ºC warmer than the west coast of North America at the same latitude due to the poleward flowing Leeuwin Current.

AR-associated evaporation is close to zero along the west coast of North America during the landfall because of the cold SST and high specific humidity.

Because of the unique SST fields caused by the Leeuwin Current, the evolution of AR-induced air-sea fluxes could be different from that in the northeast Pacific.

Enhancement of Leeuwin Current caused by landfalling ARs



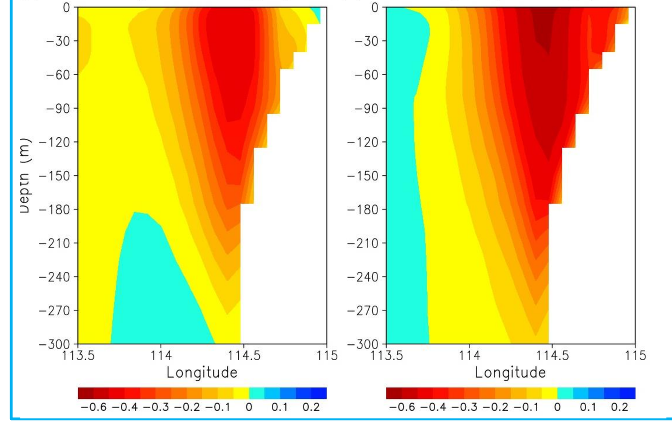


Figure 2. Upper left: Total column integrated water vapor (mm) on September 9, 2015 derived from SSMI data Upper right: Winds at 10 m height on September 9. Lower left: a) The composite meridional velocity (m/s) along 34ºS on Day − 5. (b) Same s (a) except on Day 0. Adapted from Shinoda et al. (2020).

Strong anomalous surface winds associated with ARs generate strong anomalous coastal currents which largely enhance poleward flowing Leeuwin Current.

Since Leeuwin Current carries warm waters from the tropics, it may influence SSTs through poleward heat advection.

However, AR-associated winds also enhance evaporative cooling (latent heat flux).

Warming or cooling during landfalling AR events?

Purpose of this study

Quantify air-sea flux and SST variability associated with ARs over the southeast Indian Ocean based on the analysis of global datasets of air-sea fluxes and AR characteristics. In particular, the role of relatively warm SSTs maintained by the poleward flowing Leeuwin Current is emphasized. Also, Temporal variations of coastal air-sea fluxes and SSTs associated with landfalling ARs are investigated.

Data

Surface fluxes from the Objectively Analyzed air-sea Fluxes (OAFlux) product and winds from Cross-Calibrated Multi-Platform wind vector analysis (CCMP) version 3.

Case studies

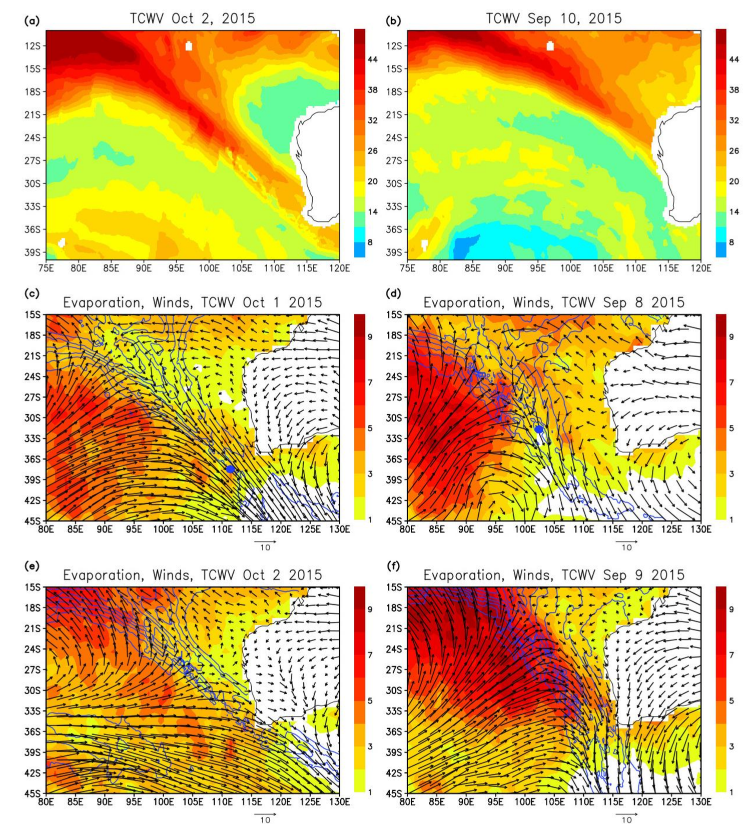


Figure 3. (a) Total column integrated water vapor (mm) on October 2, 2015 derived from SSMI data. (b) Same as (a) except for September 10. (c) Surface evaporation (mm/day: shading), winds (m/s) at 10 m (arrows), and total column integrated water vapor (contour) on October 1, 2015. (d) Same as (c) except for September 8. (e) Same as (c) except for October 2. (f) Same as (c) except for September 9.

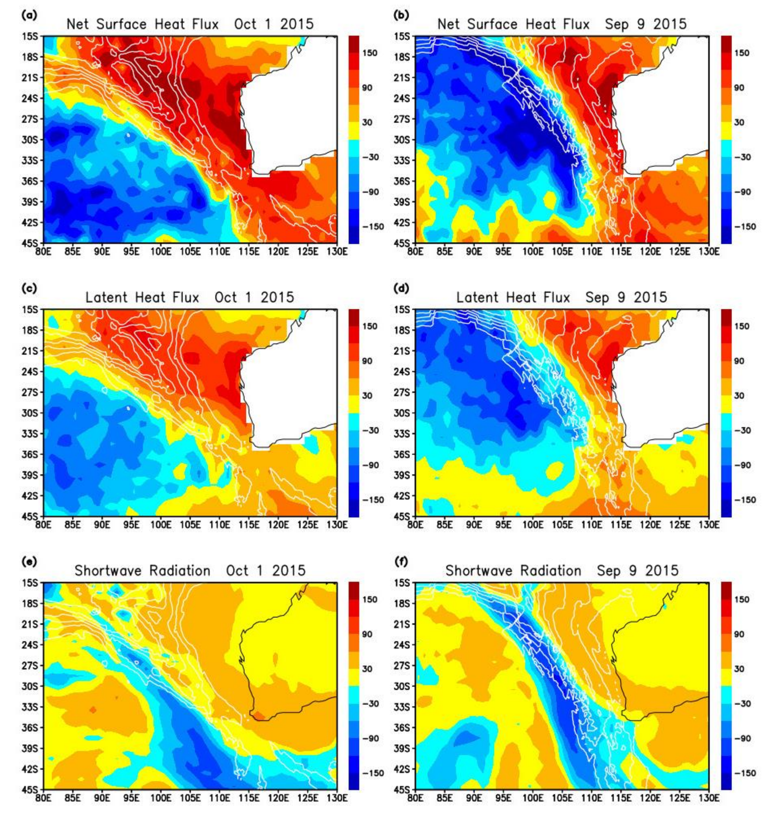


Figure 4. (a) Net surface heat flux anomaly and total column integrated water vapor (contour) on October 1, 2015. The positive values indicate the downward anomalous heat flux (warming the ocean). (b) Same as (a) except on September 9. (c) Surface latent heat flux on October 1, 2015. (d) Same as (c) except on September 9. (e) Surface shortwave radiation on October 1, 2015. (f) Same as (e) except on September 9.

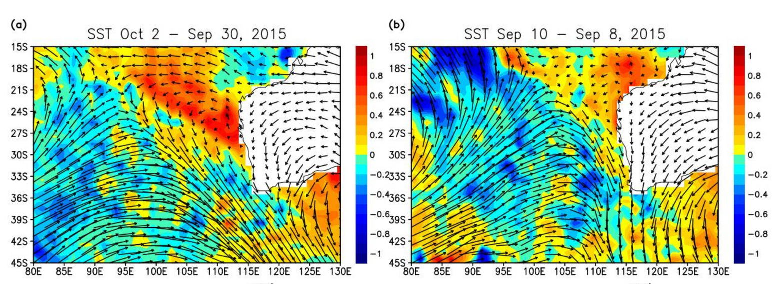


Figure 5. (a) The difference of SST (ºC: shading) between the periods before (September 30, 2015) and after (October 2) the landfalling of AR event, and winds (m/s) at 10 m (arrows) on October 1, 2015. (b) Same as (a) except for the SST difference between September 10 and September 8 and winds on September 9.

ARs are associated with a cyclonic circulation on the western poleward side of ARs and anti-cyclonic circulation on the eastern equatorward side of ARs. Strong surface evaporation (and thus cooling due to surface latent heat flux) is found on the western poleward side of ARs whereas evaporation is small on the eastern equatorward side of ARs. Strong surface winds are found in a large area of the cyclonic circulation, but the specific humidity is also high near the AR center, and thus the maximum evaporation is found on the western poleward side of AR where winds are still strong but the air is drier than the AR center. Spatial variations of SST changes are similar to the net surface heat flux anomalies during these AR events, suggesting that these SST changes are primarily produced by surface heat fluxes. The latent heat flux mostly contributes to the net surface heat flux as these fluxes show the similar spatial pattern.

Composite analysis

Air-sea flux evolution in the open ocean area

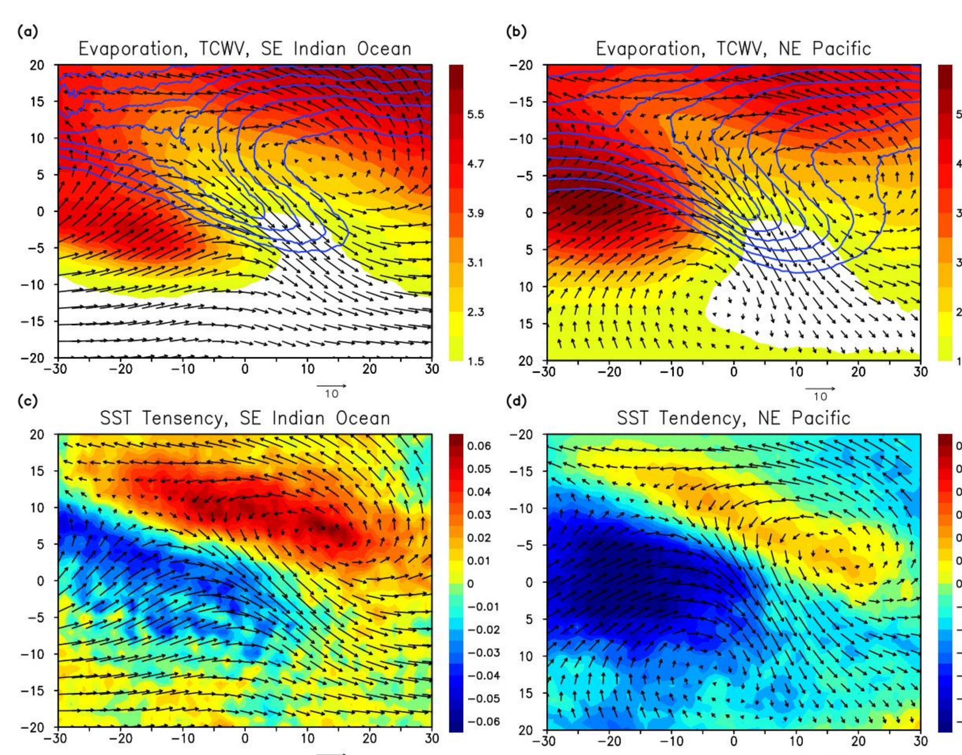


Figure 6. (a) Composite of evaporation (mm/day: shading), TCWV (mm: contour), and winds at 10 m (m/s: arrows) for the period 2011–2015 over the Southeast Indian Ocean (70ºE-120ºE, 15ºS-40ºS). (b) Same as (a) except for the Northeast Pacific (170ºW-120ºW, 15ºN-40ºN). The plot is flipped upside down such that the direction of the North Pole is downward to compare with (a). (c) Composite of SST tendency (C/day: shading) and winds at 10 m (m/s: arrows) for the period 2011–2015 over the Southeast Indian Ocean (70ºE-120ºE, 15ºS-40ºS). (d) Same as (c) except for the Northeast Pacific (170ºW-120ºW, 15ºN-40ºN). The plot is flipped upside down as in (b).

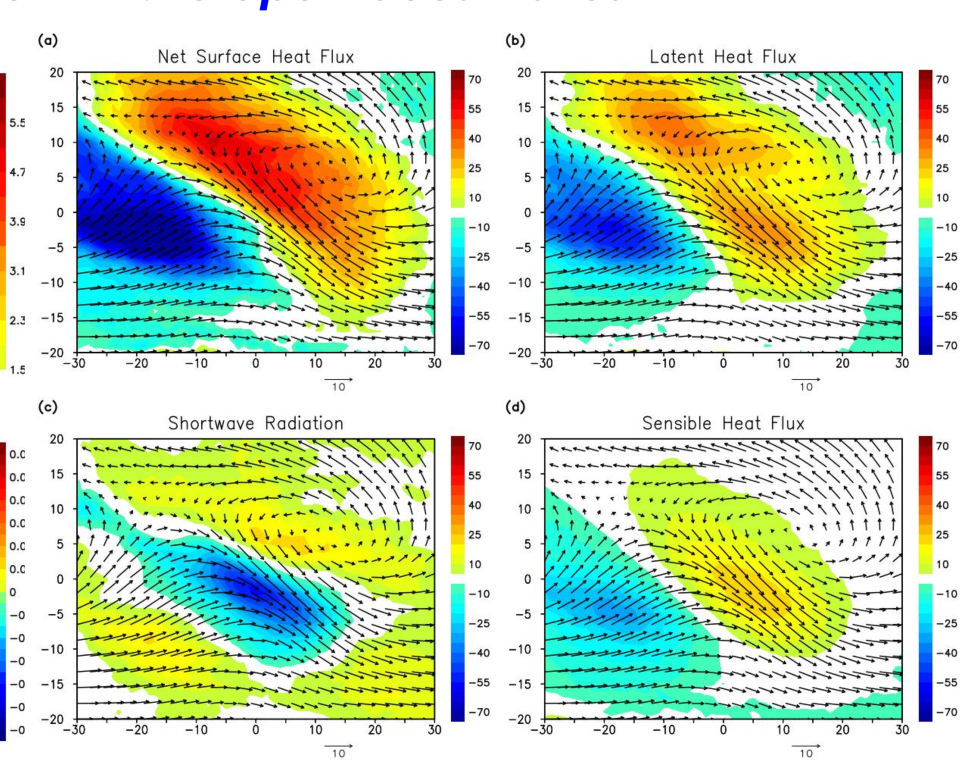


Figure 7. (a) Composite of net surface heat flux anomaly (W/m^2: shading) and wind at 10 m (m/s: arrows). The positive values indicate the downward anomalous heat flux (warming the ocean). (b) Same as (a) except for latent heat flux anomaly (W/m^2). (c) Same as (a) except for shortwave radiation anomaly (W/m^2). (d) Same as (a) except for sensible heat flux anomaly(W/m^2).

Spatial structure of composite evaporation, SST tendency, and surface heat fluxes are consistent with case studies. Large surface evaporation is found in the western poleward side of AR upstream areas. SST cooling (warming) is found on the western poleward (eastern equatorward) side of AR core. The spatial pattern of composite net surface heat flux anomaly is similar to that of SST tendency, and it is primarily determined by the latent heat flux.

The overall spatial structure of evaporation and SST tendency are similar in the southeast Indian Ocean and the northeast Pacific

Evolution along the coast

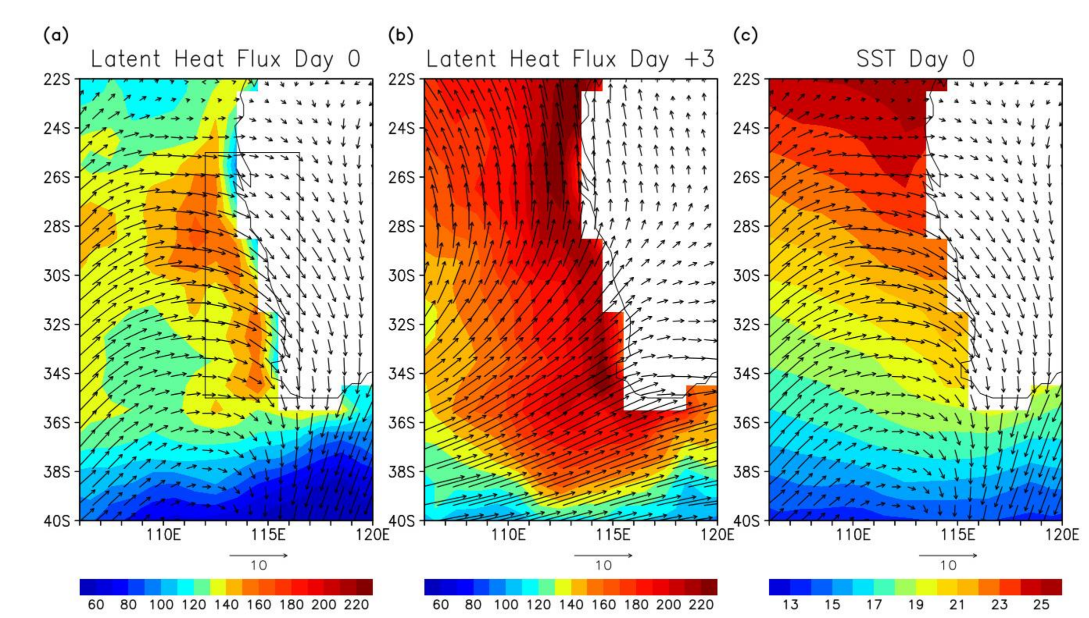


Figure 8. (a) Surface latent heat flux (W/m^2) and 10 m winds (m/s) along the west coast of Australia on Day 0. (b) Same as (a) except on Day +3. (c) Same as (a) except for SST.

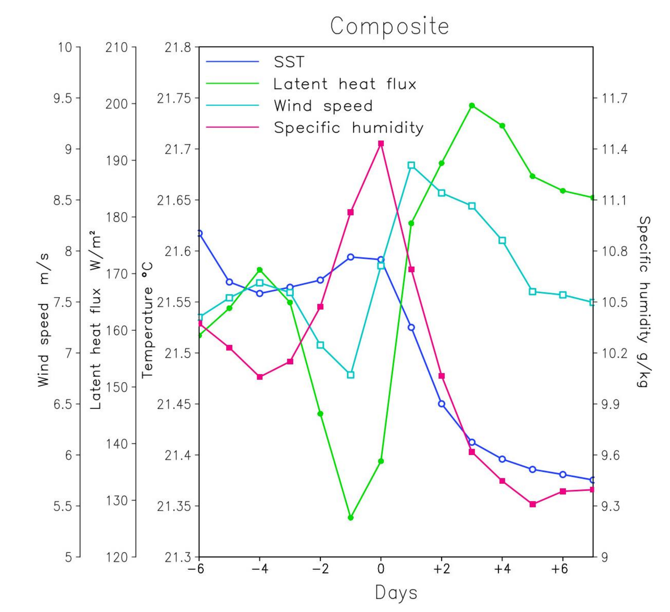


Figure 9. Time series of composite SST (ºC; blue line with open circle mark), latent heat flux (W/m^2; green line with closed circle mark), wind speed (m/s; cyan line with open square mark), and specific humidity (g/kg; red line with closed square mark) averaged over the area 112ºE-116.5ºE, 25ºS-35ºS (a box area in Fig. 8a).

A significant latent heat flux induced by ARs is evident along the west coast of Australia due to the relatively warm surface waters maintained by the poleward flowing Leeuwin Current. The latent heat flux during the landfall is about 130 W/m^2 (Day -1), and it increases up to about 200 W/m^2 (Day +3) after the landfall, resulting in about 70 W/m^2 changes. The SST cooling of about 0.2°C for the 5-day period occurs after the AR landfall.

Acknowledgments: This research is supported by NASA OVWST Grant 80NSSC23K0982.