Fingerprints of atmospheric rivers in marine heatwaves

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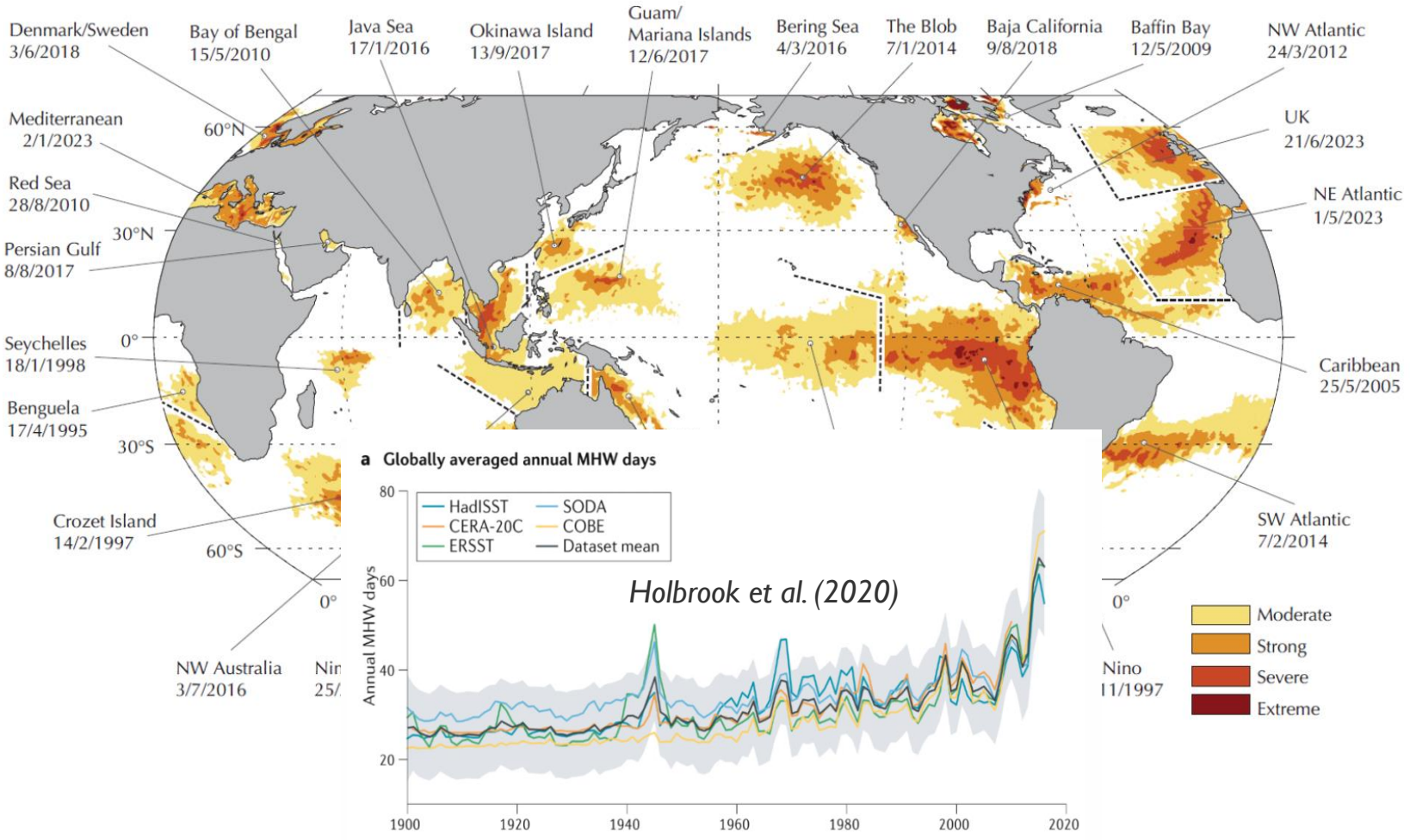
Marine heatwaves (MHWs)

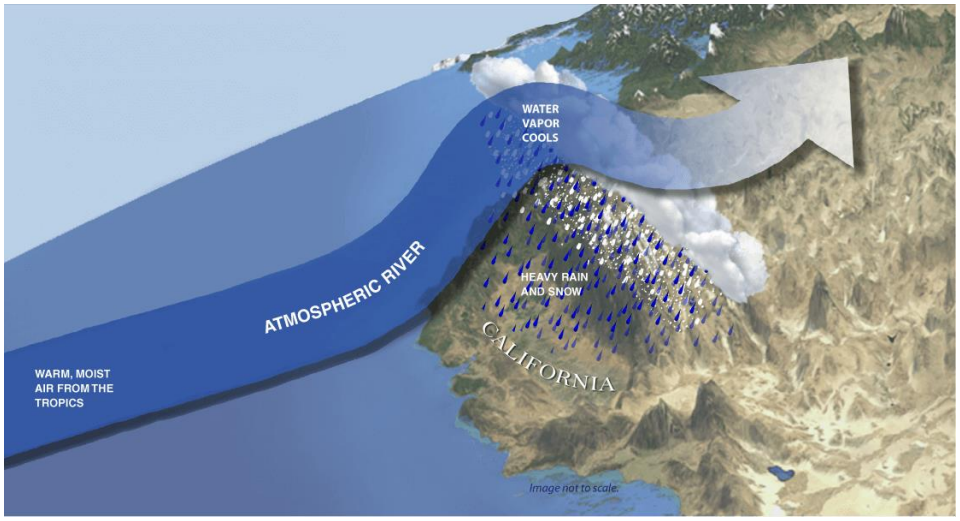
Marine heatwaves (MHWs) are characterized by anomalously warm sea surface temperatures (SSTs), typically lasting for weeks or even years.



Marine heatwaves (MHWs)

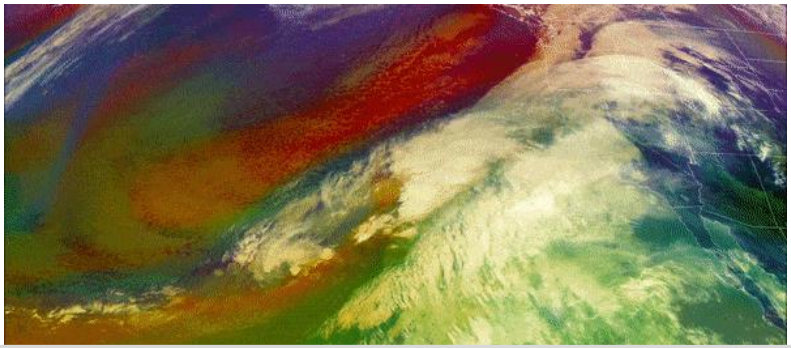
- **Large-scale climate variability modes (e.g., ENSO, PDO, NAO)**
  – modulate the likelihood and characteristics of MHWs by altering background oceanic and atmospheric states
  (e.g., Capotondi et al., 2022; Gregory et al., 2024; Hobday et al., 2023; Scannell et al., 2016)
- **Short-lived, intense weather systems (e.g., blocking highs, tropical cyclones)**
  – shape the development and persistence of MHWs through transient air-sea interactions
  (e.g., Chen et al., 2014; Neal et al., 2022; Overland et al., 2001)

Atmospheric rivers (ARs):
"Rivers in the sky"—long, narrow corridors of concentrated moisture transport



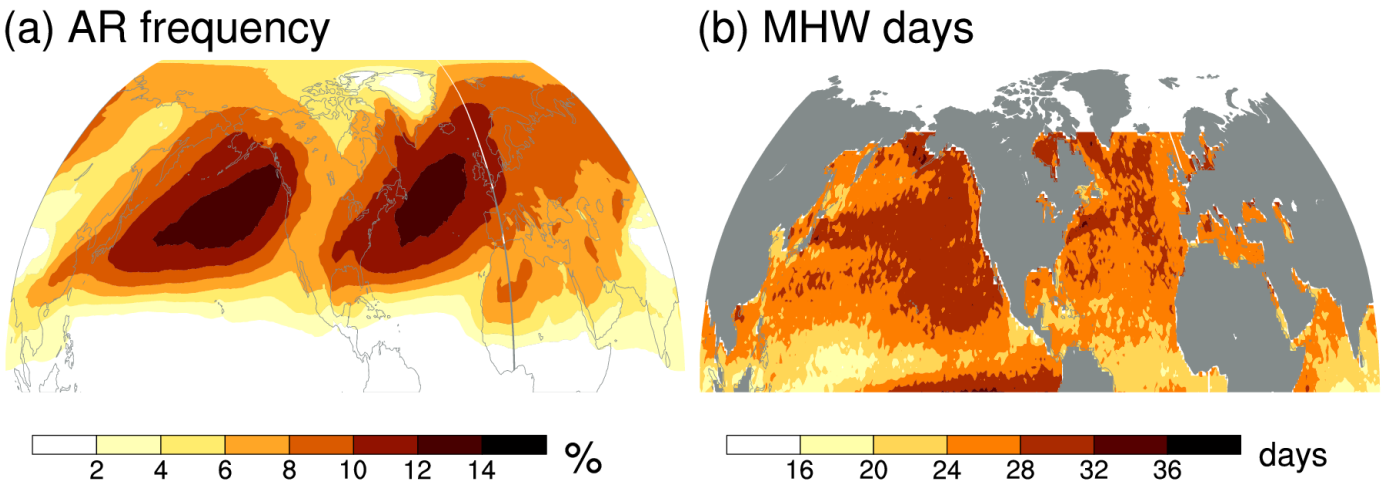
Schematic of an AR making landfall over California

Spatial Co-occurrence of ARs and MHWs



What is the relationship between ARs and MHWs?

Climatology

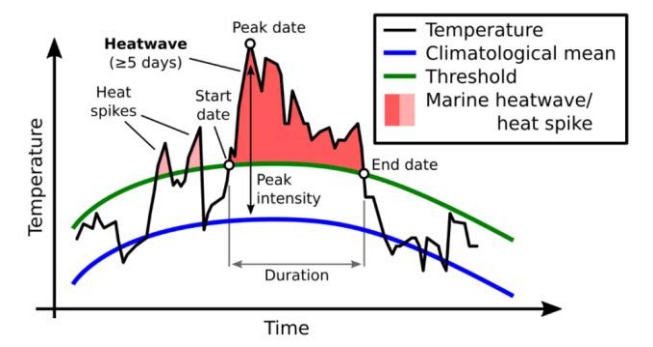


Both MHWs and ARs are especially active and impactful in the Northern Hemisphere, particularly the midlatitude ocean basins.

The relationship between MHWs and ARs

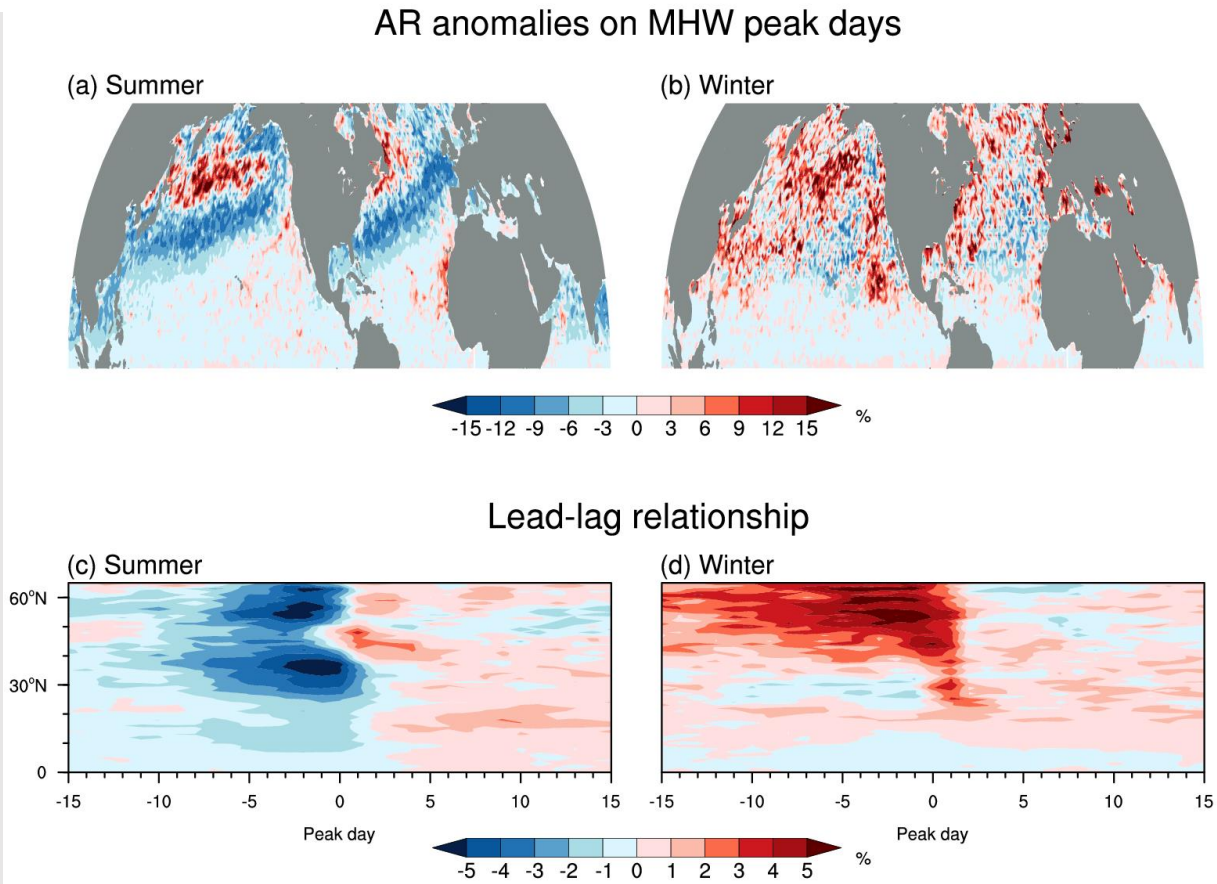
- **MHW definition** (Hobday et al., 2016)

Daily SST > 90th percentile for ≥5 days



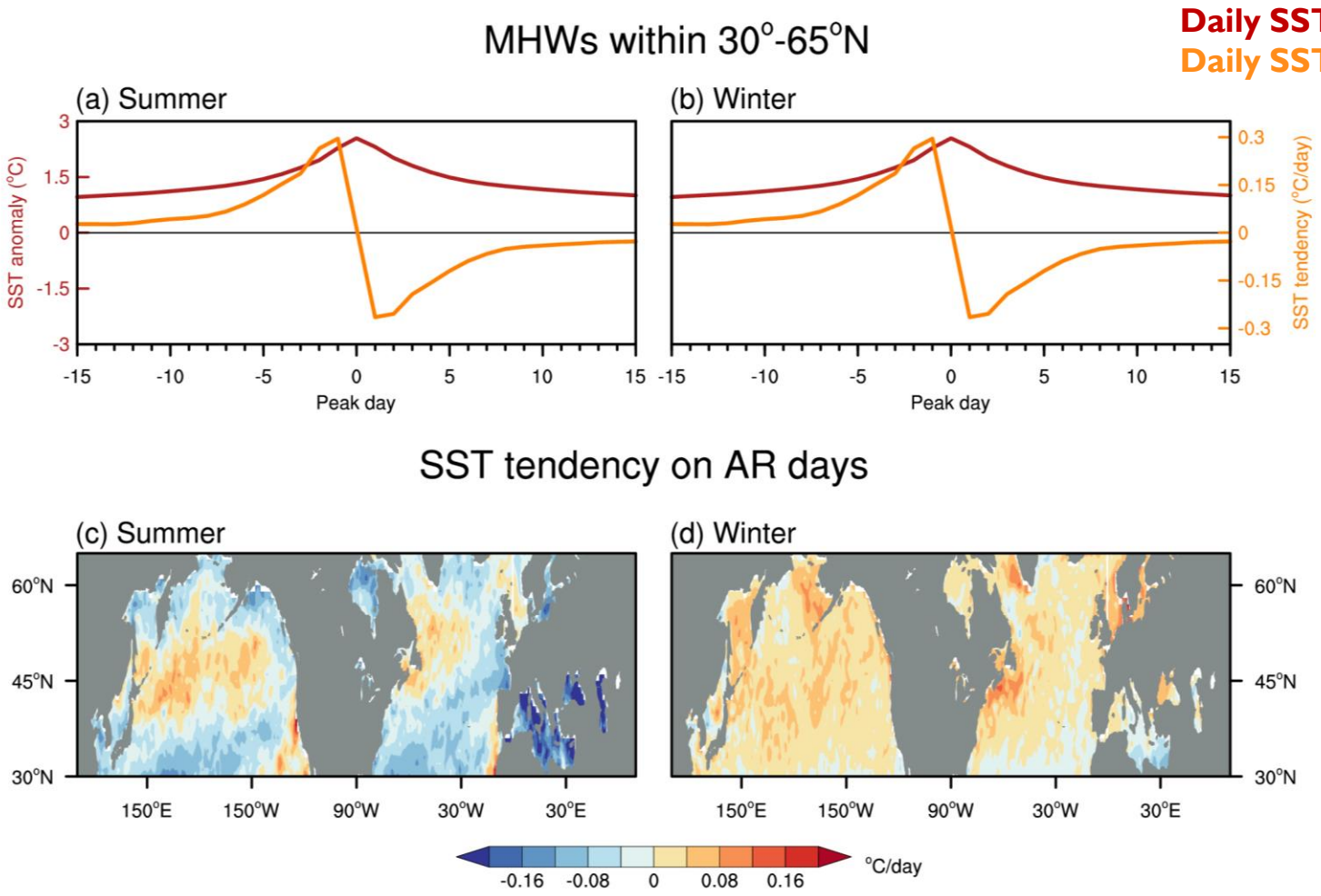
- **AR definition** (Guan & Waliser, 2024)

• 6-hourly vertically integrated water vapor transport (IVT) > 250 kg/m/s
• Length > 2000 km
• Width < 1000 km



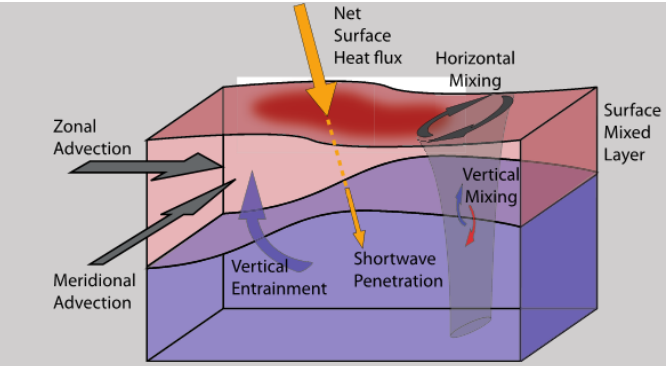
ARs precede MHWs and show strong seasonality

The role of ARs in the development of MHWs

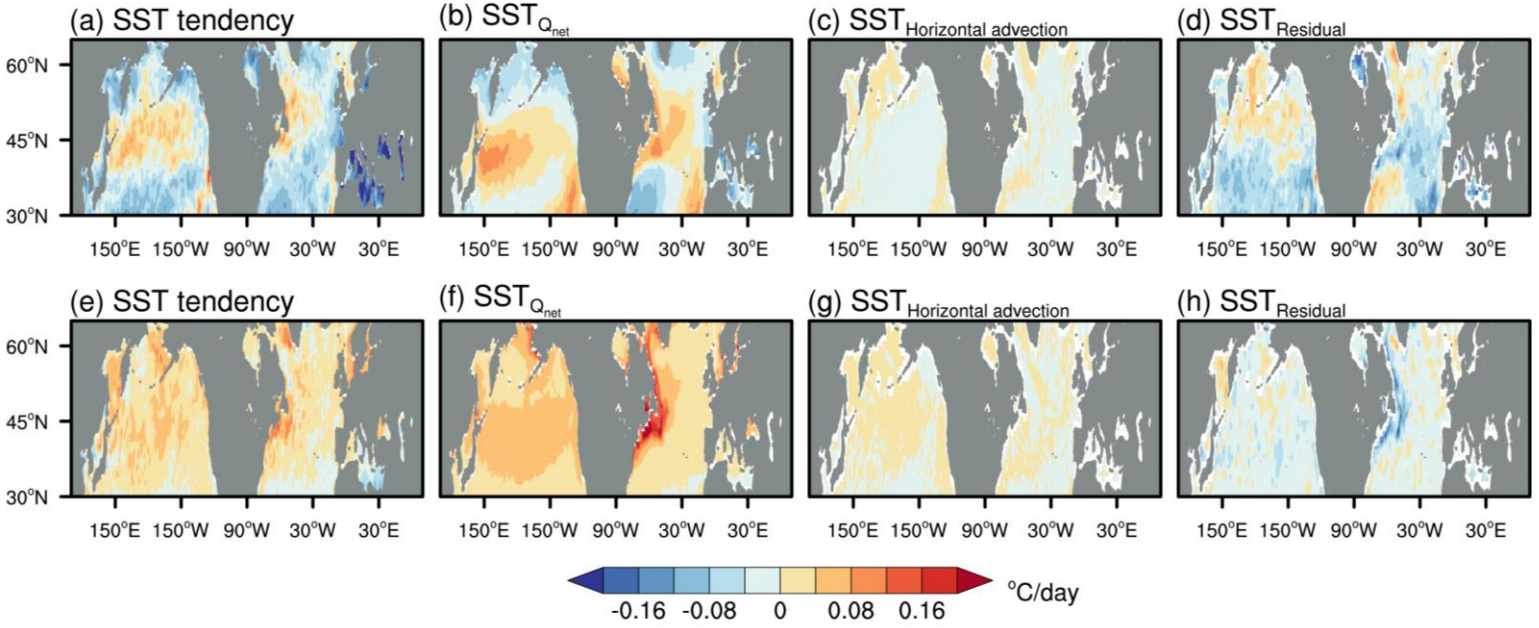


ARs-induced SST tendency exhibits a strong seasonality

Ocean mixed-layer heat budget analysis on AR days



$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho C_p h} - \overrightarrow{v_h}.\nabla_h T - \varepsilon$$

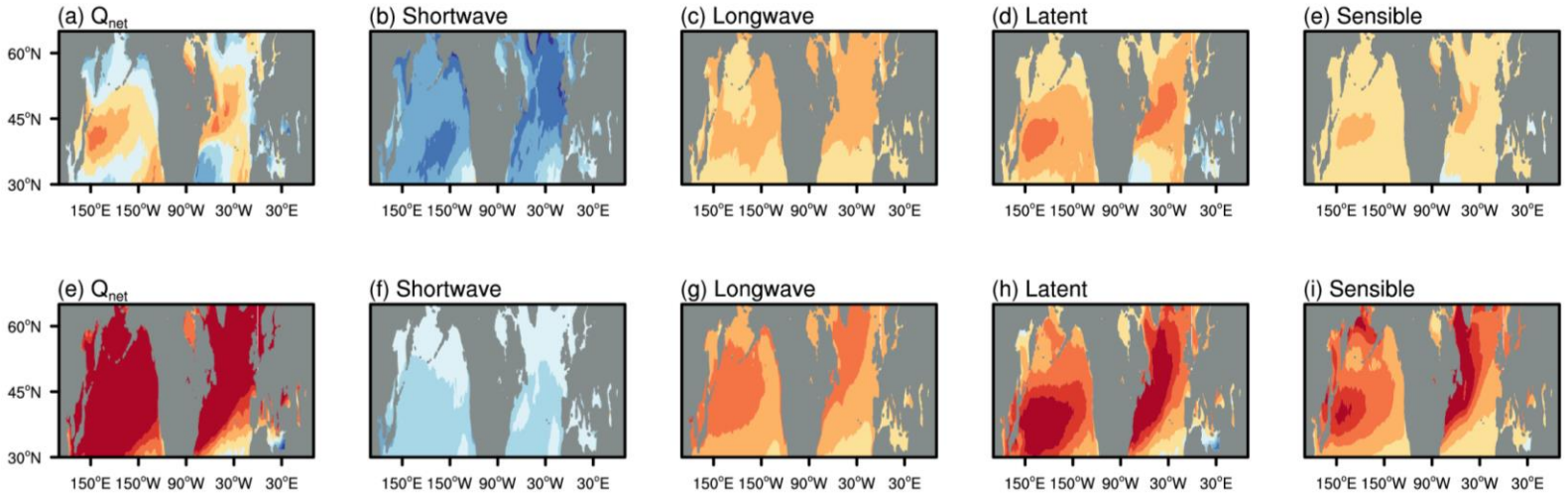


Net surface heat flux (Q_{net}) clearly emerges as the dominant driver in both summer and winter

Decomposition of Q_{net} on AR days

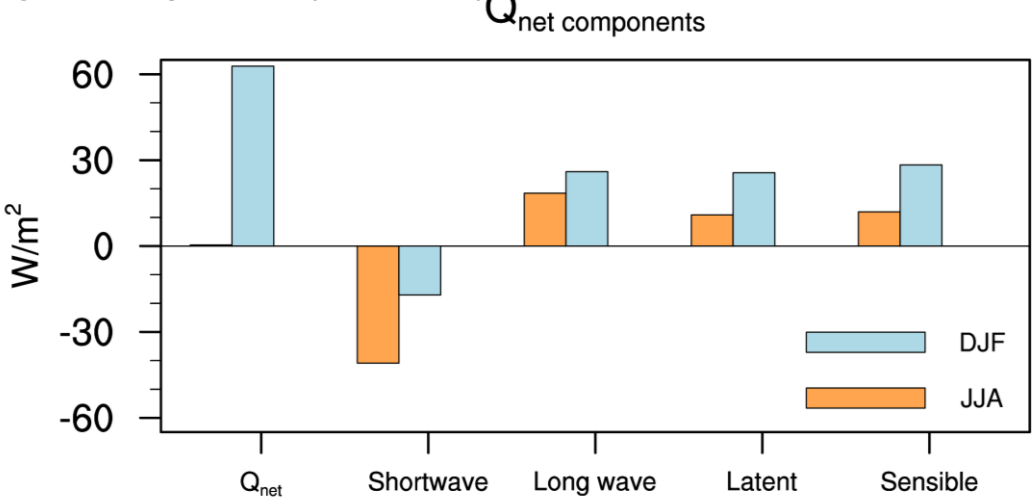
Summer

Winter



Positive: downward (air→sea)

Negative: upward (sea→air)



From summer to winter:

Upward Shortwave ↓

Downward Longwave ↑

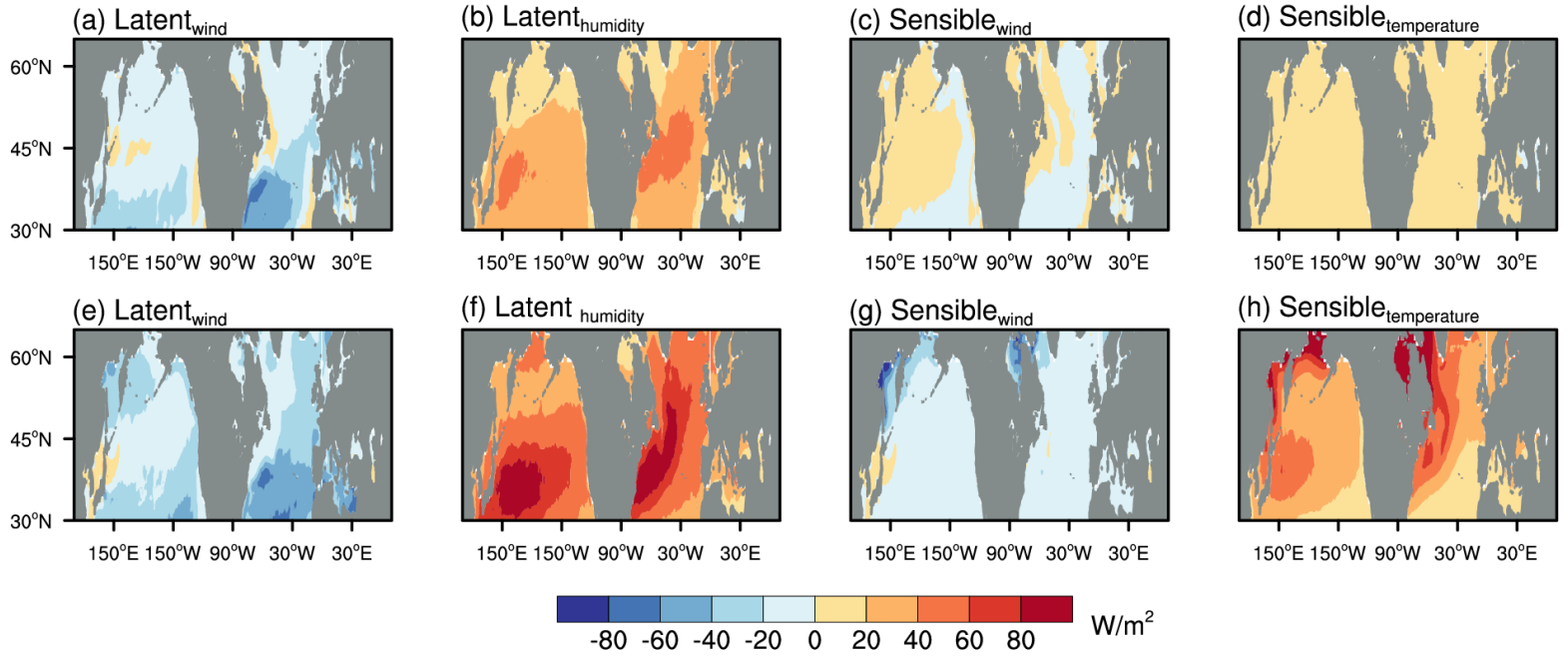
Downward Latent & Sensible ↑

Decomposition of turbulent heat flux on AR days

$$LH = \rho L_v C_e U(q_s - q_a) \sim \rho L_v C_e U'(q_s - q_a) + \rho L_v C_e \bar{U}(q'_s - q'_a)$$

$$SH = \rho c_p C_h U(T_s - T_a) \sim \rho c_p C_h U'(T_s - T_a) + \rho c_p C_h \bar{U}(T'_s - T'_a)$$

Wind-driven LH | **Humidity gradient-driven LH** | **Wind-driven SH** | **Temperature gradient-driven SH**



Summer

Winter

Net downward turbulent heat flux anomalies primarily arises from thermodynamic processes (humidity/temperature gradient)

Decomposition of turbulent heat flux on AR days

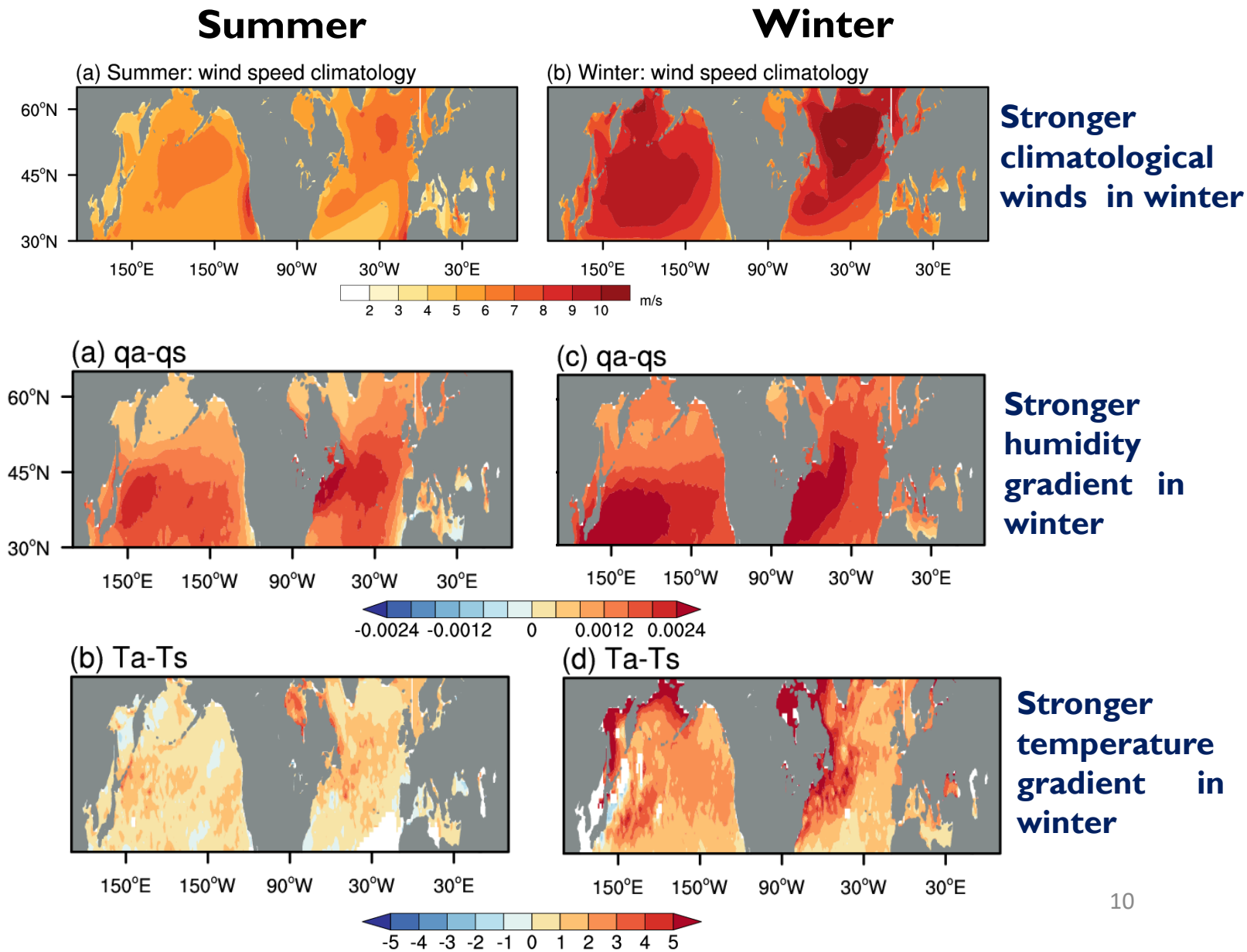
$\rho L_v C_e \overline{U}(q'_s - q'_a)$

$\rho c_p C_h \overline{U}(T'_s - T'_a)$

$\overline{U}$

$q'_s - q'_a$

$T'_s - T'_a$



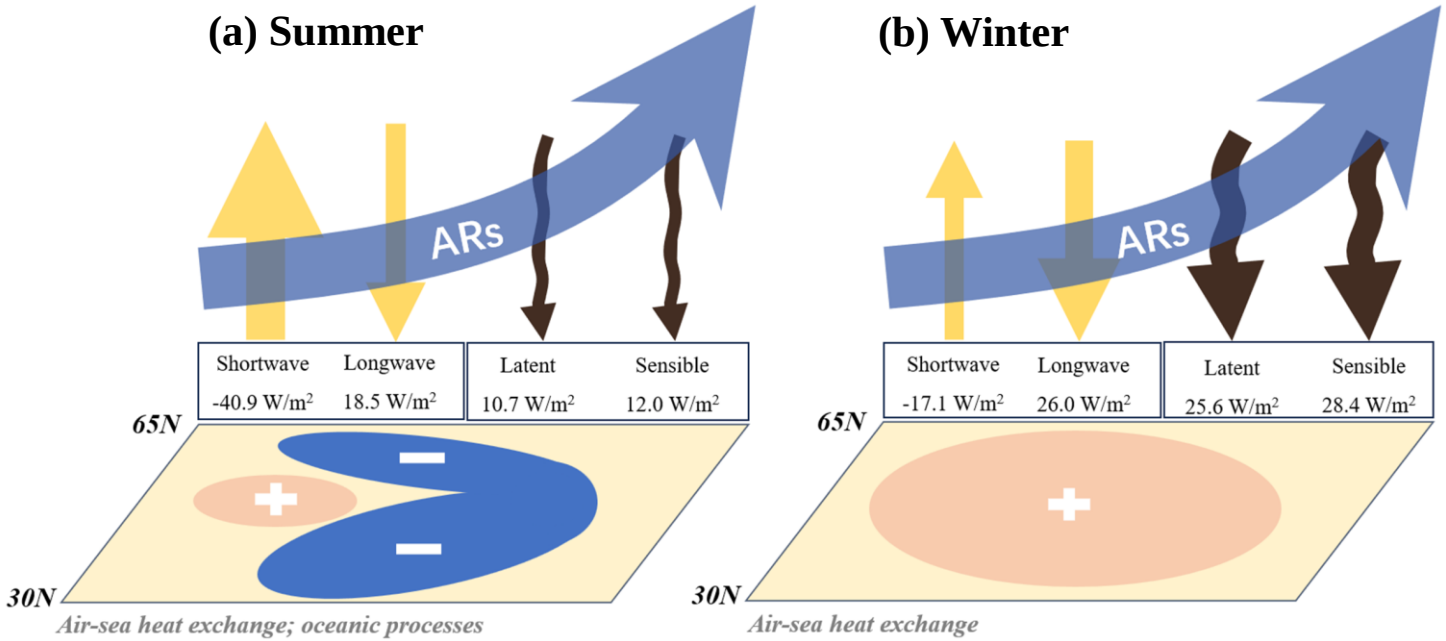
Stronger climatological winds in winter

Stronger humidity gradient in winter

Stronger temperature gradient in winter

Summary

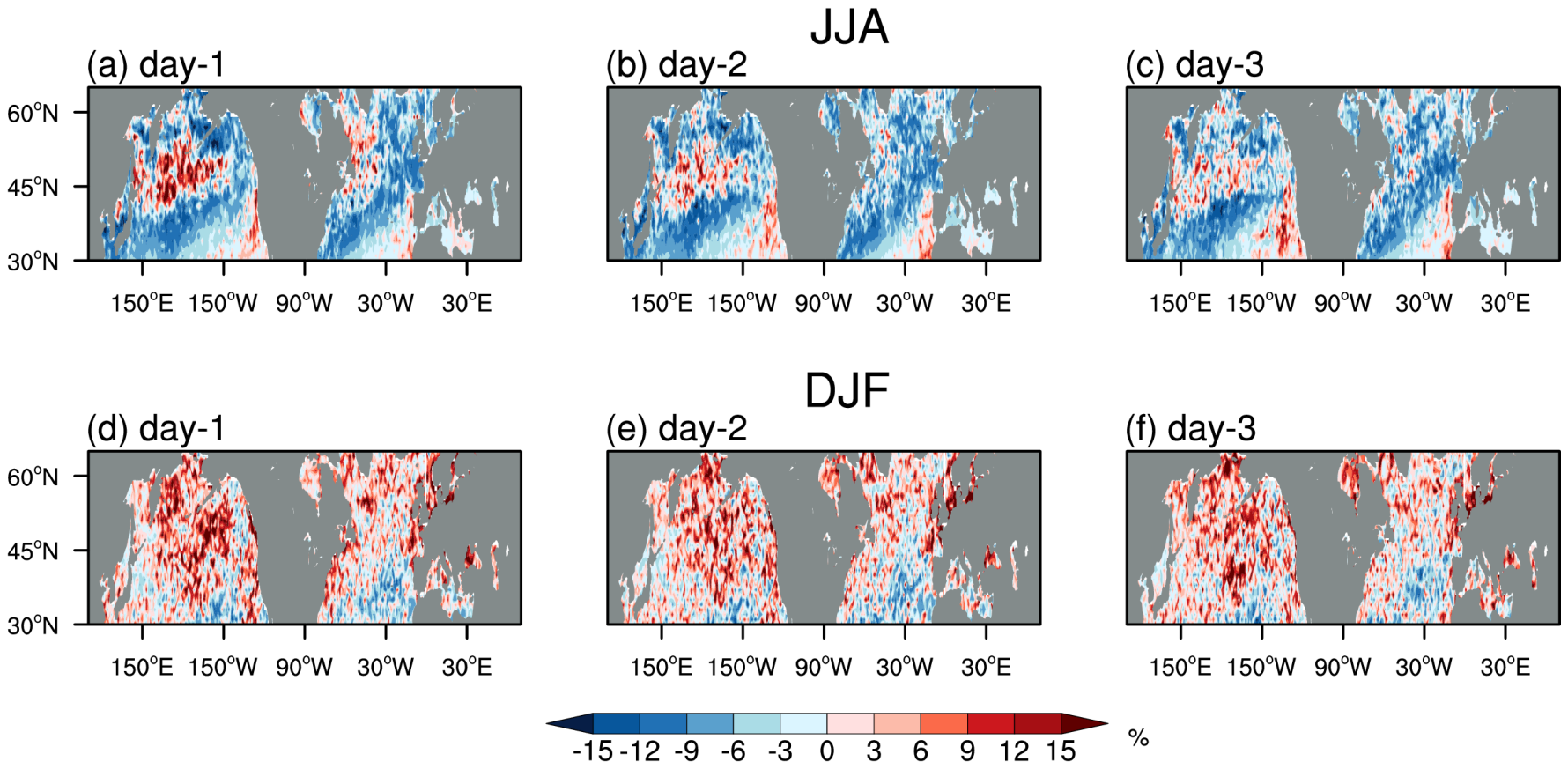
Seasonally modulated fingerprints of ARs in MHWs



- **AR impacts on MHWs exhibit a strong seasonal dependence, with a horseshoe-shaped AR anomaly pattern detected in boreal summer while a monopole AR anomaly pattern in winter.**
- **This can be largely attributed to a delicate balance in AR-induced changes in turbulent heat fluxes and radiative fluxes, modulated by seasonal cycle.**

The relationship between MHWs and ARs

1 to 3 days before MHW peak days



ARs appears before MHWs and exhibits a strong seasonality