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An anomalous atmospheric river linked to the late June 2021 western North America heatwave

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Atmospheric rivers (ARs) are long and narrow bands of enhanced water vapour flux concentrated in the lower troposphere. Many studies have documented the important role of cold-season ARs in producing heavy precipitation and triggering extreme flooding in many parts of the world. However, relatively little research has been conducted on the warm-season ARs and their impacts on extreme heatwave development. Here we show an anomalous warm-season AR moving across the North Pacific and its interaction with the western North American heatwave in late June 2021. We call it an “oriental express” to highlight its capability to transport tropical moisture to the west coast of North America from sources in Southeast Asia. Its landfall over the Alaska Panhandle lasted for more than two days and resulted in significant spillover of moisture into western Canada. We provide evidence that the injected water vapour was trapped under the heat dome and may have formed a positive feedback mechanism to regulate the heatwave development in western North America.

The concept of the atmospheric river (AR) as a filamentary structure in atmospheric water vapour transport has been around since the 1990s¹⁻³, and can even be dated back to the conceptual models of “warm conveyor belt” in the 1970s⁴⁻⁶ and “moist tongue” in the 1930s⁷.

ARs are typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone, and frequently lead to heavy precipitation when they are forced upward by mountains or frontal forcing^{8,9}. Along the west coast of North America (NA), high-impact ARs often arrive in the cold season when weather is dominated by the strong onshore flow of Pacific airstreams. Some of these ARs are also known as “pineapple express” storms for their apparent origin in the tropical area near Hawaii¹⁰⁻¹³. Their landfall on mountainous areas can produce extremely heavy precipitation events and may trigger hazardous floods, mudslides, and avalanches. Intense ARs are rare over the northeast Pacific in the warm season, when a ridge of high pressure tends to lie off the west coast of NA. Here we investigate an anomalous summer AR which moved across the North Pacific and made a prolonged landfall over the Alaska Panhandle during June 24-26, 2021. Our analysis indicates that this AR was capable of transporting tropical warm moist air from Southeast Asia into the NA continent. We have called it an “oriental express” to emphasize this unique connection. The track for this express was controlled mainly by an unseasonably deep Aleutian Low in conjunction with a stable North Pacific High. A trans-Pacific wave train was also identified in the mid-troposphere. Its connection with the boreal summer intraseasonal oscillation in Southeast Asia¹⁴ and the western NA heatwave have been examined in a separate study¹⁵. In this article, we provide an in-depth analysis of the hydrometeorological impacts of the AR in NA. It is shown that the 3-day landfall of the AR produced only moderate to locally heavy precipitation over the Alaska Panhandle. The more important effect was its inland-penetration across the Pacific Coast Ranges which transported moisture into western Canada. Given that water vapour is the dominant greenhouse gas in the atmosphere¹⁶⁻²⁰, we establish a possible link between the moisture trapped under the ridge of high pressure and the heat wave development in western NA. Correlation analysis shows that the 5-day (26-30 June) mean air temperatures are positively correlated with the mean water vapour content across Canada. Although the cause of these positive correlations may be attributed mainly to the fact that as temperatures rise, more water vapour can be present in the atmosphere before saturation occurs, there is evidence for a positive moisture feedback through

the greenhouse effect that contributed to the heatwave intensification in western Canada in late June 2021. Our verification analysis also shows that when a numerical weather prediction (NWP) model failed to predict the inland penetration of the AR, it also failed to predict the severity of the following heatwave in western Canada.

Oriental express: a trans-Pacific AR with its origin in Southeast Asia

ARs are often defined based on the vertically integrated vapour transport (IVT) derived from specific humidity and wind profiles (Methods)^{1-3,21-23}. Based on the ERA5 global reanalysis²⁴, the IVT distributions over the North Pacific basin valid at 0000 UTC June 21-26, 2021 are shown in Fig. 1. The corresponding distributions of sea level pressure (SLP), 500-hPa geopotential height (Z500), and integrated water vapour (IWV) are shown in Figures S1-S3 in the supplementary information (SI). Here one can apply either the IVT₂₅₀ or the IVT₅₀₀ scheme outlined in the Methods section for AR identification. Figure 1 characterises the northeastward advance of a substantial AR across the North Pacific basin. In general, this AR was driven mainly by a twin-engine system consisting of the anomalously deep Aleutian Low and the stable subtropical North Pacific High. It was linked to the Asian summer monsoon system through most of its lifespan. This connection is the inspiration for calling it the oriental express, analogous to the pineapple express that brings warm and moist air from tropical sources near Hawaii to the west coast of NA.

Two ARs can be identified in the North Pacific at 0000 UTC June 21, 2021 (Fig. 1a). The one in the east was driven by a cyclone in the Gulf of Alaska (L₁₀₀₃) with a strong anticyclone to its south (H₁₀₂₉). It made landfall on the Alaska Panhandle about 12 hours earlier and was rapidly dissipating. The major AR was the oriental express driven by the Aleutian Low (L₉₇₉) into the northeast Pacific from the west. The minimum SLP at the cyclonic centre was 979 hPa, which was 31 hPa below the climatological mean value of 1010 hPa at that location (Fig. 2a). On the northern flank of this AR there were also two secondary cyclones (L₁₀₀₁ and L₉₉₅) centred at

(28°N, 125°E) and (39°N, 148°E), respectively. They were locally interacting with the AR and helped pump moisture from the South China Sea into the AR system. The North Pacific High spawned a secondary centre west of the 180th meridian (H_{1021}). Anticyclonic flow around this western centre transported warm moist air from the tropical western Pacific into the AR system. These features were maintained through the following two days as the Aleutian Low moved eastward across the 180th meridian and gradually weakened (Fig. 1b,c).

The Aleutian Low re-strengthened rapidly through June 23rd with the minimum SLP falling to 973 hPa around 0000 UTC June 24 as the AR made landfall on the Alaska Panhandle (Fig. 1d). With a strong and stable anticyclone to its southeast, this AR remained quasi-stationary in the northeast Pacific for more than 24 hours (Fig. 1e), and began to dissipate and disconnect with the Asian monsoon system around 0000 UTC June 26 (Fig. 1f). It was able to transport significant heat and moisture inland across the Pacific Coast Ranges that separate Alaska from western Canada (Fig. 1e,f). Note that the highest mountain in Canada (and the second highest in North America), Mount Logan, is located this region (5959 m, 60.57°N, 140.41°W).

Anomalous atmospheric patterns

To reveal the atmospheric processes responsible for driving the oriental express across the North Pacific (Fig. 1), we calculated the 5-day (June 21-25, 2021) mean anomalies of SLP, IWV, and Z500 with respect to their 30-year (1991-2020) climatology. As shown in Fig. 2a, the North Pacific High off the west coast of NA dominates the SLP distribution in the climatological map (line contours) for this early summer period. Its western extension into the subtropical northwest Pacific forms an important component of the East Asian summer monsoon²⁵. Around this time, the Aleutian Low has often reached its minimum intensity or virtually disappeared²⁶. This was not the case in 2021. In Fig. 2a, the lowest 5-day mean SLP anomaly is -21.5 hPa in the extratropical North Pacific. It was mainly this anomalous extratropical cyclone in conjunction

with the stable North Pacific High that created the strong horizontal pressure gradient needed to force the northeastward advance of the oriental express from the subtropical northwest Pacific.

The two bands of large positive IWV anomalies in Fig. 2b indicate that the tropical export from the Asian summer monsoon was capable of contributing a large amount of moisture to the oriental express as it moved across the North Pacific basin. Some authors have argued that ARs may be considered as the footprints left behind on the cyclone pathway, and local sources are primarily responsible for the high water vapour content within the AR core²⁷⁻²⁹. The current understanding is that strong ARs are capable of pumping moisture out of tropical regions and incorporating midlatitude sources of water vapour along their paths^{30,31}.

The anomaly pattern of Z500 in Fig. 2c reveals a well-defined train of Rossby waves propagating from the subtropical northwest Pacific into the extratropical Northern Hemisphere. It provides a physical explanation to the intensification of the Aleutian Low that drove the oriental express across the North Pacific basin. Previous studies have shown that this wave train can be linked to phase 7 of the boreal summer intraseasonal oscillation in Southeast Asia^{14,15}.

Orographic precipitation and cross-mountain moisture transport

Landfalling ARs are capable of producing heavy precipitation in mountainous areas, especially in the cold season with water vapour supplied by tropical moisture sources^{8,11,23,32-37}. ARs in the warm season should produce less orographic precipitation because the warmer atmosphere can contain more water vapour before condensation begins than can a cooler atmosphere. The AR depicted in Fig. 1 was intercepted by the Pacific Coast Ranges when it made landfall over the Alaska Panhandle during June 24-26, 2021. This prolonged landfall did not produce extremely heavy precipitation. Figure 3a shows the 3-day total precipitation amounts from this event. The maximum amount was reported in the Alaska Panhandle area, and was only 121 mm. Nevertheless, there were a few flooding events in late June 2021 that could be attributed to this

AR, not because of heavy rainfall but from warm advection associated with the system leading to a significant build-up of ice melt^{38,39}.

Another explanation for the precipitation inefficiency of this AR is the spillover of moisture and hydrometeors from the windward into the lee side of the mountains. We have seen in Fig. 1 that this AR penetrated deep into western Canada after its landfall. Figure 3b presents a vertical cross-section of the AR over the northeast Pacific valid at 0000 UTC June 25. It shows that, although the AR core was located near 1000 m ASL, the air column between 2000 and 5000 m contained a large amount of water vapour that was available for transport across the Pacific Coast Ranges. Some condensates generated by the orographic uplift on the windward side within this layer may also have been carried to the leeside where the descending airstreams would tend to dissipate cloud and lessen any potential rainfall through re-evaporation. The leeward cloud dissipation can be seen in the satellite imagery given in the SI (Fig. S4).

The possible AR impact on the western North America heatwave

The warm and moist air transported by the AR from the Pacific Ocean into western Canada was trapped under a ridge of high pressure in the upper troposphere (see Fig. S2 in the SI). These processes could be essential for the heat dome development, i.e., the build-up of an exceptionally hot air mass when high pressure aloft prevented warm air below from rising and the subsidence associated with the high pressure caused further warming by compression⁴⁰. This heat dome was responsible for the extreme heatwave in western North America from late June through mid-July 2021^{15,41}.

Figure 4 shows the anomalies of 5-day mean IWV and temperatures in North America during June 26-30, 2021, together with their local correlation coefficients based on 43-year (1979-2021) data from the ERA5 reanalysis. The positive IWV anomalies (Fig. 4a) in western

Canada can be attributed jointly to the AR-induced moisture transport from the North Pacific Ocean and the local evaporation/evapotranspiration under the heat dome. A narrow band with even larger positive IWV anomalies across central and eastern NA was caused by a strong AR formed in the Gulf of Mexico during this period; here the moisture was not locally trapped and the AR produced some heavy precipitation events as it moved across the continent.

The anomalies of 5-day mean near-surface temperature (T_{2m}) and lower-tropospheric mean temperature ($\bar{T}$, see Methods for definition) are shown in Fig. 4b. The intensity and extent of the heatwave are indicated by the significant positive temperature anomalies in western NA. As shown in the SI (Fig. S4), the extreme heatwave started in Washington State and spread rapidly southward into Oregon and northward across BC and Alberta in western Canada. It generated some of the highest temperatures ever recorded in this region, including the new Canadian record of 49.6°C measured at Lytton, BC on June 29, 2021⁴¹.

The correlation maps in Fig. 4c,d show that across Canada the air temperatures are positively correlated with the local IWVs during June 26-30. In many regions, including northern BC on the leeward side of the Pacific Coast Ranges, the correlation coefficients are higher than 0.80. Although correlation does not necessarily imply causation, it is reasonable to assume that the moisture injected by the AR into western Canada had a positive feedback loop to amplify the heatwave development in late June 2021. It is well known that water vapour is the dominant greenhouse gas that traps infrared radiation in the atmosphere¹⁶⁻¹⁹. Therefore, the moisture trapped under the heat dome is able to cause further warming of the lower troposphere. This argument can be justified by noting that the build-up of IWV anomalies in late June 2021 was slightly ahead of the rapid temperature increases over western Canada, as evident from a detailed comparison between Figures S5 and S6 in the SI. On the other hand, one could also argue that

the IWV build-up in western Canada was coincidental, because the advection in of moisture from the AR happened because of the building upper ridge that provided the trajectory for the moisture. In addition, it is possible to have more water vapour in an air parcel at a higher temperature than at a lower temperature, because the saturation vapour pressure is uniquely determined by temperature (with little pressure dependence).

An indirect support for our above argument of positive feedback loop comes from our verification of the operational predictions of this AR event. Figure 5 shows the IVT distributions valid at 0000 UTC June 25, 2021 as analysed and predicted by the Global Deterministic Prediction System (GDPS)⁴² of Environment and Climate Change Canada. The analysed AR over the northeast Pacific (Fig. 5a) was well predicted by the NWP model with lead times (LT) up to 96 hours (Fig. 5b,c). The predictions with LT = 144 and 192 hours (Fig. 5d,e) could still be considered as good guidance for the arrival time and landfall location of the AR. However, the deep inland-penetration of the AR into western Canada was not correctly predicted by these model runs, which were initialized at 0000 UTC June 19 and 17, respectively. The model run initialized 10 days ahead (Fig. 5f) gave a poor prediction of landfall location of the AR at 0000 UTC June 25.

Figure 6 shows the analysed and predicted T_{2m} valid at 0000 UTC June 27. We see that the temperature pattern in western Canada was well predicted with LT = 144 h, i.e. from the NWP model initialized at 0000 UTC June 21 (Fig. 6a vs Fig. 6b). It is shown in Fig. 5 that the inland-penetration of the AR at 0000 UTC June 25 was also correctly predicted by the model run initialized as early as June 21. The model initialized at 0000 UTC June 19 or 17 provided poor guidance for both the AR penetration (Fig. 5d,e) and the temperature distribution (Fig. 6c,d) in western Canada.

Concluding remarks

We have described an anomalous warm-season AR moving across the North Pacific Ocean in late June 2021 and dubbed it the oriental express. This system brought tropical moisture to the west coast of NA from the summer monsoon system in Southeast Asia. It was driven by an anomalous atmospheric pattern, which may have been forced by the boreal summer intraseasonal oscillation in Southeast Asia^{14,15}. The landfall of this AR over the Alaska Panhandle injected a large amount of moisture into western Canada. Some of this water vapour accumulated under a ridge of high pressure and may have formed a positive feedback loop to enhance the heatwave development over western NA during late June and early July 2021. A rapid attribution analysis has pointed out that the occurrence of this extreme heatwave is virtually impossible without human-caused climate change⁴¹. Our results provide evidence that moisture must be considered when assessing heatwave development in a changing climate. Because ARs are narrow corridors of strong horizontal water vapour transport concentrated in the lower atmosphere, their landfall not only has the potential to produce heavy orographic precipitation, but is also possible to contribute to the development of an inland heat dome in summer.

Although one of the main issues in this study is assessing whether the moisture advected into western Canada via the AR has a significant effect on the heatwave, our analysis is not able to quantify this impact to an order of magnitude. Some questions remain to be addressed, such as

- 1) How much of the anomalous water vapour was transported in, and how much was contributed locally through evaporation and evapotranspiration?
- 2) What is the timescale over which adding water vapour to the atmosphere leads to enhanced temperatures locally at the surface?

Probably these issues can be addressed in a more quantitative manner by running a model with and

without the water vapour feed into western Canada and analysing what differences arise in the heatwaves produced by the model. This approach is beyond the scope of this article.

Methods

Atmospheric river identification methods. The vertically integrated vapour transport (IVT) and integrated water vapour (IWV) are two commonly used variables in AR analysis. They can be defined as^{1,3,23}

$$\text{IVT} = \sqrt{Q_u^2 + Q_v^2}, \quad \text{IWV} = g^{-1} \int_{p_t}^{p_b} q dp, \quad (1)$$

where

$$Q_u = g^{-1} \int_{p_t}^{p_b} u q dp, \quad Q_v = g^{-1} \int_{p_t}^{p_b} v q dp. \quad (2)$$

In the above equations, g is the acceleration due to gravity ($g = 9.81 \text{ m s}^{-2}$), q is the specific humidity, u and v are the zonal and meridional velocities, respectively, and p is the air pressure. The vertical integration is from the top ($p = p_t$) to the bottom ($p = p_b$) of the atmosphere. Q_u and Q_v represent the zonal and meridional components of the integrated water vapour flux, respectively.

There have been many AR identification and tracking algorithms in the literature based mainly on the distribution of IVT, IWV, or a combination of the two⁴³. In this study we choose a simple method called the IVT₂₅₀ scheme⁴⁴, which defines an AR as a contiguous region ≥ 2000 km in length with $\text{IVT} \geq 250 \text{ kg m}^{-1}\text{s}^{-1}$. For warm-season ARs, one may also increase the criterion to $500 \text{ kg m}^{-1}\text{s}^{-1}$ to get an IVT₅₀₀ scheme.

Data sources. The main data sources for this study are the ERA5 global reanalysis²⁴ and the operational numerical weather prediction (NWP) output from the Global Deterministic Prediction System (GDPS) of Environment and Climate Change Canada⁴². The ERA5 has hourly output on a $0.25^\circ \times 0.25^\circ$ latitude-longitude grid; we only use the 0000 and 1200 UTC data in June from 1979 to 2021. The GDPS uses a Yin-Yang grid with an approximate horizontal spacing of 15 km. It provides weather forecasts up to 10 days, and is run twice daily initialized at 0000 and 1200 UTC, respectively. Both the ERA5 output and the GDPS analysis are considered as observations.

The daily precipitation data used to produce Fig. 3a are from the Climate Prediction Center (CPC) Global Unified Gauge-Based Analysis⁴⁵ provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their web site at <https://psl.noaa.gov/data/grades/d/data.cpc.globalprecip.html>. The land-based data are available on a $0.5^\circ \times 0.5^\circ$ latitude-longitude grid.

500-hPa geopotential height and mean temperature in the lower troposphere.

Meteorologists prefer to express the horizontal pressure gradient force in the mid-troposphere as the gradient of geopotential along the 500-hPa pressure surface. This level is, on average, around 5.5 km above sea level. It is also common to consider mean temperature in the lower troposphere as a function of the geopotential thickness between this level and the 1000-hPa level. This mean temperature ($\bar{T}$) can be defined as

$$\bar{T} = \frac{g(Z_{500} - Z_{1000})}{R \ln(2)}, \quad (3)$$

where R is the gas constant for dry air ($R = 287 \text{ J kg}^{-1} \text{ K}^{-1}$), Z_{500} and Z_{1000} are the geopotential heights at the levels of 500 and 1000 hPa, respectively.

258

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263

264 Competing interests

265 The authors declare no competing interests.

266

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Fig. 1 | The IVT distributions valid at 0000 UTC June 21-26, 2021. Data are from the ERA5

reanalysis. The vector represents the integrated water vapour flux (Q_u, Q_v) defined in Methods.

$IVT = (Q_u^2 + Q_v^2)^{1/2}$. The major high and low centres of SLP in the Pacific Ocean are marked by letters “H” and “L” with their local maximum/minimum SLP values (in hPa).

Fig. 2 | The anomalies of 5-day (June 21-25, 2021) mean SLP, IWV, and 500-hPa geopotential height (colour contours) with respect to their 30-year (June 21-25, 1991-2020) climatology (line contours). The intervals of line contours are 4 hPa in (a), 5 kg m^{-2} in (b), and 60 m in (c), respectively. All data are from the ERA5 reanalysis.

Fig. 3 | (a) The distribution of 3-day precipitation amount during June 24-26, 2021. The daily precipitation data are obtained from the CPC Global Unified Gauge-Based Analysis (see Methods for description). The 72-hour period ends at 0600 UTC in Canada and at 1200 UTC June 26 in the United States. **(b) A northwest-southeast vertical cross section valid at 0000 UTC June 25, 2021 based on the ERA5 reanalysis.** The cross-section location is indicated by a red line in the embedded box. Colour-filled contours represent the specific humidity. Red dashed lines are potential temperature contours (intervals: 5K). Blue solid lines are elevations ASL (intervals: 1000 m). Winds are indicated by the conventional wind barbs.

Fig. 4 | The anomalies of 5-day (June 26-30, 2021) mean IVW and air temperatures,

together with the correlation coefficients between them. All data are from the ERA5

reanalysis. The anomalies are calculated based on the 30-year (June 26-30, 1991-2020)

climatology. In (a), the IWV anomalies over western Canada can be attributed to the water

vapour transport from the oriental express. In (b), the lower-tropospheric averaged temperature (

$\bar{T}$) anomalies are represented by line contours with intervals of 2°C , and the 2-metre

temperature (T_{2m}) anomalies are colour-filled. In (c) and (d), the correlation coefficients are

calculated from 43-year (1979-2021) data; the coefficient values between -0.30 and 0.30 are

statistically insignificant with p-values beyond 0.05 based on the two-tailed Student t-test.

Fig. 5 | Distributions of the IVT valid at 0000 UTC 25 June 2021 based on the Canadian GDPS operational outputs. (a) The GDPS analysis. (b)-(f) The GDPS predictions with different lead times (LT).

Fig. 6 | Distributions of the 2-metre temperature valid at 0000 UTC June 27, 2021 based on the Canadian GDPS operational outputs. (a) The GDPS analysis. (b)-(d) The GDPS predictions with different lead times (LT).

Supplementary Files

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