Diagnosing Primary Condensation Rate Attributed to the Moisture Convergence: Applications to Atmospheric River Analysis and Extratropical Storm Classification

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Abstract

Abnormally heavy precipitation events can lead to numerous hazards, including flooding, landslides, and avalanches. Their developments require a sufficient supply of moisture and some physical mechanism to produce condensation. Atmospheric rivers (ARs) defined as long and narrow corridors of strong horizontal moisture transport can provide such necessary conditions. The presence and strength of ARs are often described using the integrated water vapor (IWV) and the integrated vapor transport (IVT). However, the associated precipitation is not directly correlated with these two variables. It is the net convergence of moisture that determines the intensity of precipitation. The purpose of this study is to illustrate, in the context of AR analysis, how the converged vapor should be distributed between condensation and air moistening. A simple algorithm is proposed for estimating the heavy precipitation attributable to the IVT convergence. Bearing a strong resemblance to the Kuo-Anthes parameterization scheme for cumulus convection, the proposed algorithm calculates the large-scale primary condensation rate (PCR) as a proportion of the IVT convergence, with a reduction to account for the general moistening in the atmosphere. The amount of reduction is determined by the column relative humidity (CRH), which is defined as the ratio of IWV to its saturation counterpart. It is found that the PCR in an air column with CRH < 0.60 is negligibly small. Based on a one-year dataset from the Canadian global numerical weather prediction (NWP) model, the best cut-off value of CRH for the algorithm is 0.66. It is demonstrated that this diagnosable PCR compares well to the forecast precipitation rate given by the NWP model. Case studies are conducted to illustrate the usefulness of CRH and PCR as two complements to standard AR analysis and impact-based storm classification.

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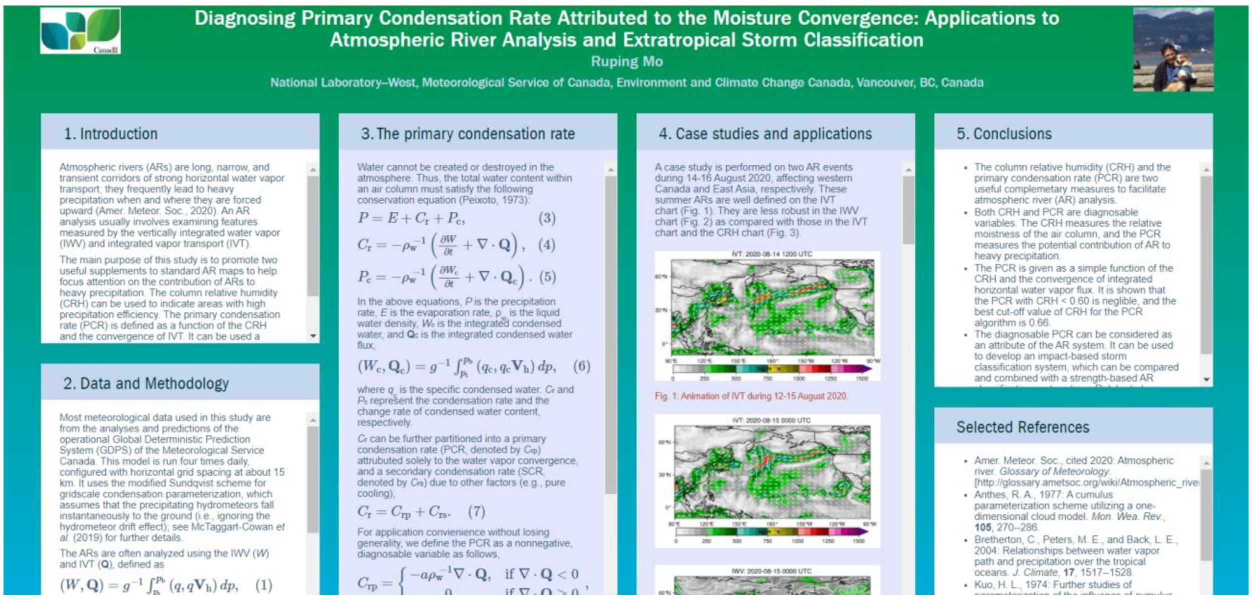

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Abstract

Abnormally heavy precipitation events can lead to numerous hazards, including flooding, landslides, and avalanches. Their developments require a sufficient supply of moisture and some physical mechanism to produce condensation. Atmospheric rivers (ARs) defined as long and narrow corridors of strong horizontal moisture transport can provide such necessary conditions. The presence and strength of ARs are often described using the integrated water vapor (IWV) and the integrated vapor transport (IVT). However, the associated precipitation is not directly correlated with these two variables. It is the net convergence of moisture that determines the intensity of precipitation. The purpose of this study is to illustrate, in the context of AR analysis, how the converged vapor should be distributed between condensation and air moistening. A simple algorithm is proposed for estimating the heavy precipitation attributable to the IVT convergence. Bearing a strong resemblance to the Kuo-Anthes parameterization scheme for cumulus convection, the proposed algorithm calculates the large-scale primary condensation rate (PCR) as a proportion of the IVT convergence, with a reduction to account for the general moistening in the atmosphere. The amount of reduction is determined by the column relative humidity (CRH), which is defined as the ratio of IWV to its saturation counterpart. It is found that the PCR in an air column with CRH < 0.60 is negligibly small. Based on a one-year dataset from the Canadian global numerical weather prediction (NWP) model, the best cut-off value of CRH for the algorithm is 0.66. It is demonstrated that this diagnosable PCR compares well to the forecast precipitation rate given by the NWP model. Case studies are conducted to illustrate the usefulness of CRH and PCR as two complements to standard AR analysis and impact-based storm classification.

1. Introduction

Atmospheric rivers (ARs) are long, narrow, and transient corridors of strong horizontal water vapor transport; they frequently lead to heavy precipitation when and where they are forced upward (Amer. Meteor. Soc., 2020). An AR analysis usually involves examining features measured by the vertically integrated water vapor (IWV) and integrated vapor transport (IVT).

The main purpose of this study is to promote two useful supplements to standard AR maps to help focus attention on the contribution of ARs to heavy precipitation. The column relative humidity (CRH) can be used to indicate areas with high precipitation efficiency. The primary condensation rate (PCR) is defined as a function of the CRH and the convergence of IVT. It can be used a diagnosable AR attribute that measures the potential precipitation rate caused by the IVT convergence.

2. Data and Methodology

Most meteorological data used in this study are from the analyses and predictions of the operational Global Deterministic Prediction System (GDPS) of the Meteorological Service Canada. This model is run two times daily, configured with horizontal grid spacing at about 15 km. It uses the modified Sundqvist scheme for gridscale condensation parameterization, which assumes that the precipitating hydrometeors fall instantaneously to the ground (i.e., ignoring the hydrometeor drift effect); see McTaggart-Cowan *et al.* (2019) for further details.

The ARs are often analyzed using the IWV (W) and IVT ($|\mathbf{Q}|$), defined as

$$(W, \mathbf{Q}) = g^{-1} \int_{p_t}^{p_b} (q, q\mathbf{V}_h) dp, \quad (1)$$

where *g* is the gravity acceleration, p_b and p_t are pressures at the base and top of an air column, *q* is the specific humidity, and $\mathbf{V}_h$ is the horizontal wind vector. In this study, p_b is the surface pressure and p_t = 200 hPa.

The integrated saturation water vapor (W_s) and the CRH ($\Re$) are given by (Bretherton et al., 2004)

$$W_s = g^{-1}\int_{p_t}^{p_b} q_s \mathrm{d}p, \qquad \Re = W / W_s, \tag{2}$$

where q_s is the saturation specific humidity.

The CRH can be used as a complementary measure in the AR analysis. It helps to identify the moist area where the precipitation efficiency is high.

The definition and algorithm for the PCR is given in Section 3.

3. The Primary Condensation Rate

Water cannot be created or destroyed in the atmosphere. Thus, the total water content within an air column must satisfy the following conservation equation (Peixoto, 1973):

$$P = E + C_r + P_c, \tag{3}$$

$$C_r = -\rho_w^{-1}\left(\frac{\partial W}{\partial t} + \nabla \cdot \mathbf{Q}\right), \tag{4}$$

$$P_c = -\rho_w^{-1}\left(\frac{\partial W_c}{\partial t} + \nabla \cdot \mathbf{Q}_c\right). \tag{5}$$

In the above equations, *P* is the precipitation rate, *E* is the evaporation rate, ρ_w is the liquid water density, W_c is the integrated condensed water, and $\mathbf{Q}_c$ is the integrated condensed water flux,

$$(W_c, \mathbf{Q}_c) = g^{-1}\int_{p_t}^{p_b} (q_c, q_c \mathbf{V}_h)\mathrm{d}p, \tag{6}$$

where q_c is the specific condensed water. C_r and P_c represent the condensation rate and the change rate of condensed water content, respectively.

C_r can be further partitioned into a primary condensation rate (PCR, denoted by C_{rp}) attributed solely to the water vapor convergence, and a secondary condensation rate (SCR, denoted by C_{rs}) due to other factors (e.g., pure cooling),

$$C_r = C_{rp} + C_{rs}. \tag{7}$$

For application convenience without losing generality, we define the PCR as a nonnegative, diagnosable variable as follows,

$$C_{\rm rp} = \begin{cases} -a\rho_{\rm w}^{-1}\nabla\cdot\mathbf{Q}, & \text{if } \nabla\cdot\mathbf{Q} < 0; \\ 0, & \text{if } \nabla\cdot\mathbf{Q} \geq 0; \end{cases} \tag{8}$$

where $0 \leq a \leq 1$. It is assumed that a fraction *a* of the total converged moisture is condensed, while the remaining fraction $(1-a)$ is stored in the air to increase the humidity (Kuo, 1974). For AR-induced heavy precipitation events, it may be safely assumed that $C_{\rm rp} \gg E + C_{\rm rs} + P_{\rm c}$.

In this study, we assume that *a* is a function of the column relative humidity ($\Re$) in the following form (*cf.* Anthes, 1977)

$$a = \begin{cases} \left(\dfrac{\Re - \Re_{\rm c}}{1-\Re_{\rm c}}\right)^n, & \text{if } \Re > \Re_{\rm c}; \\ 0, & \text{if } \Re \leq \Re_{\rm c}; \end{cases} \tag{9}$$

where $\Re_{\rm c}$ and *n* are parameters that may be empirically adjusted. In this study, we let $n=1$ and try to determine an optimal $\Re_{\rm c}$ in Section 4.

4. Case studies and applications

A case study is performed on two AR events during 14-16 August 2020, affecting western Canada and East Asia, respectively. These summer ARs are well defined on the IVT chart (Fig. 1). They are less robust in the IWV chart (Fig. 2) as compared with those in the IVT chart and the CRH chart (Fig. 3).

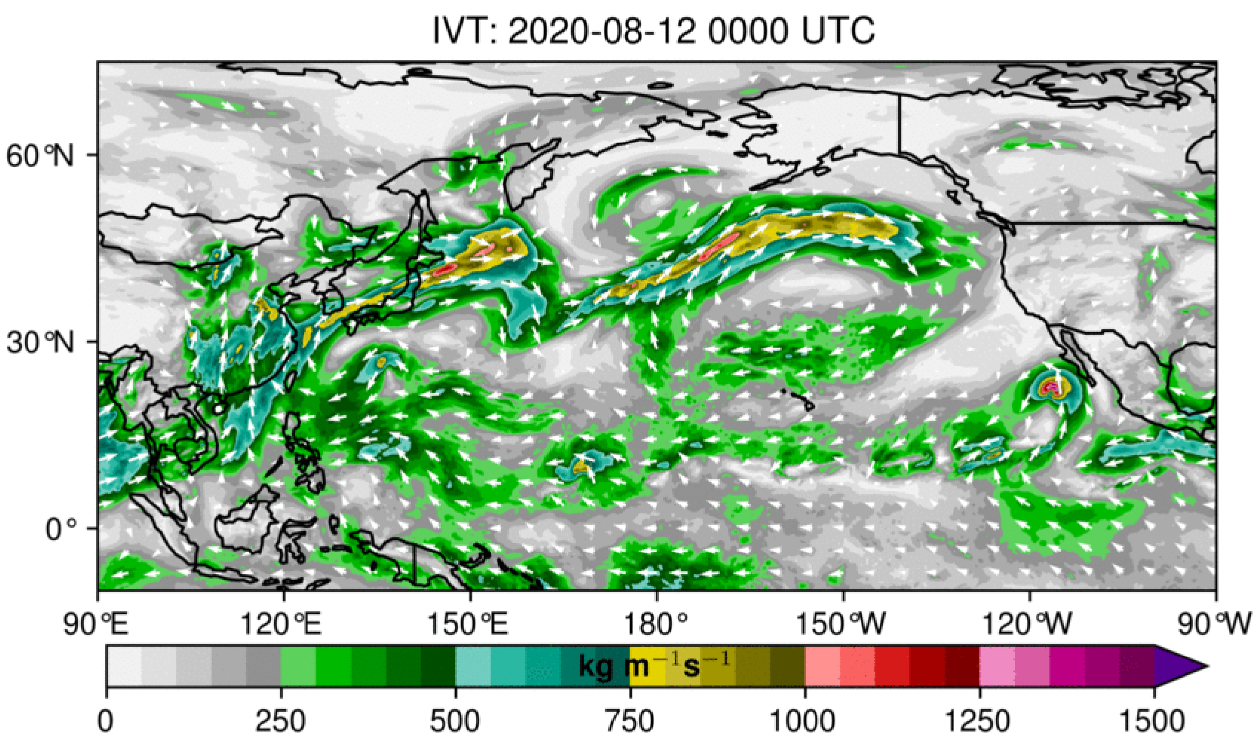

Fig. 1: Animation of IVT during 12-15 August 2020. The animated gif is available as a supplemental file.

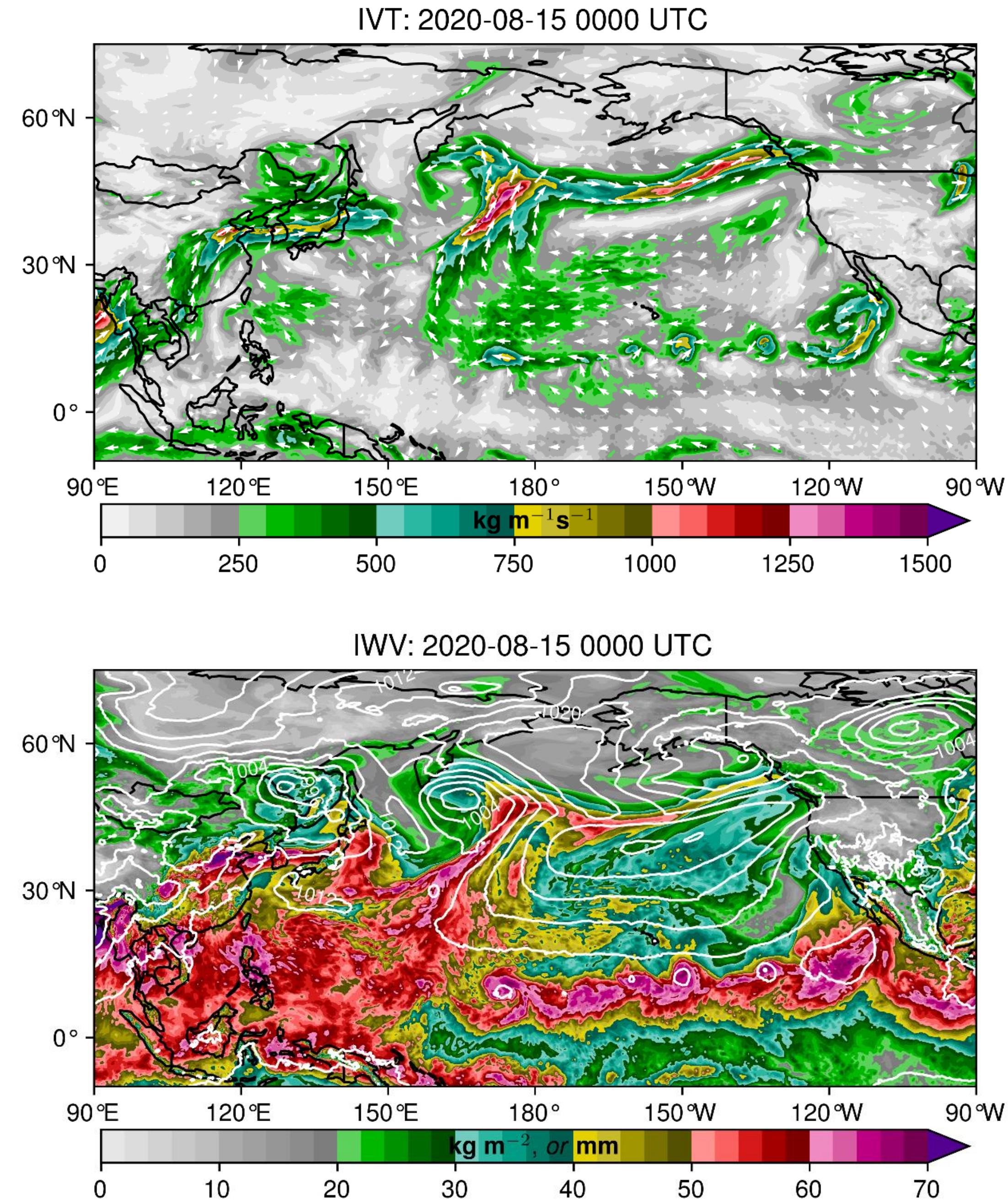

Fig. 2: IVT (top) and IWV (bottom) valid at 0000 UTC 15 August 2020.

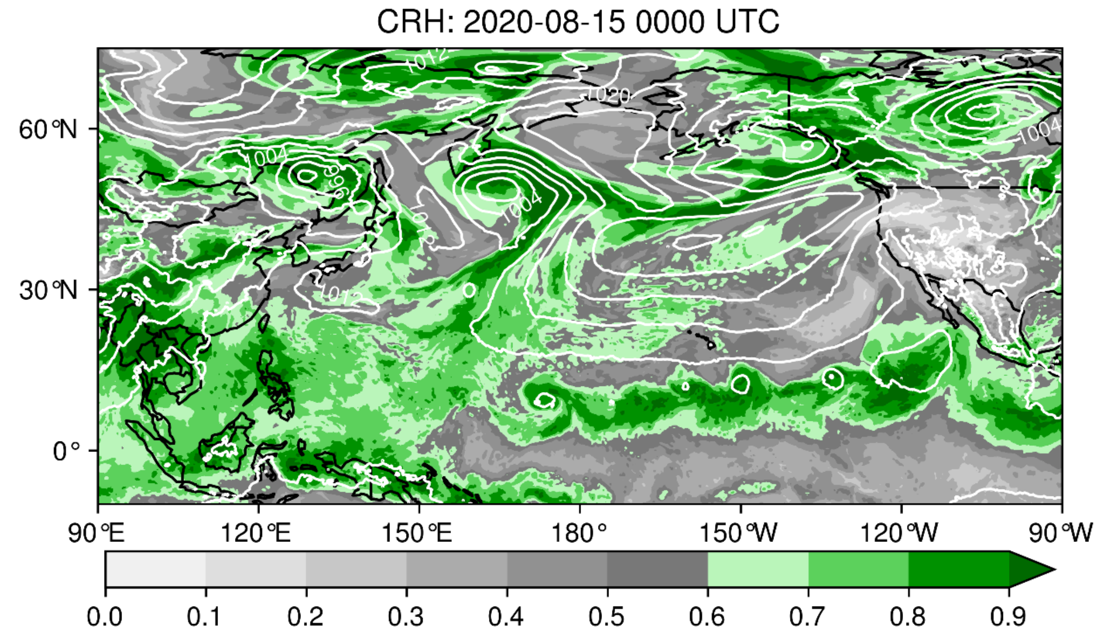

Fig. 3 CRH valid at 0000 UTC 15 August 2020.

The forecast precipitation rate (FPR) with a 24-hour lead time valid at 0000 UTC 15 August 2020 is shown in Figs. 4–6. AR-induced heavy rainfall at rates from 4 to 8 mm per hour was predicted for the Central Coast of British Columbia (BC), Canada. A narrow band of AR-induced heavy rainfall was predicted for East Asia. FPR reaches 10 to 15 mm/h in some local areas in China. Most of these predicted values were well verified by the observations. Also note that in central Canada, there was a mesoscale system producing heavy precipitation with maximum rates exceeding 25 mm/h.

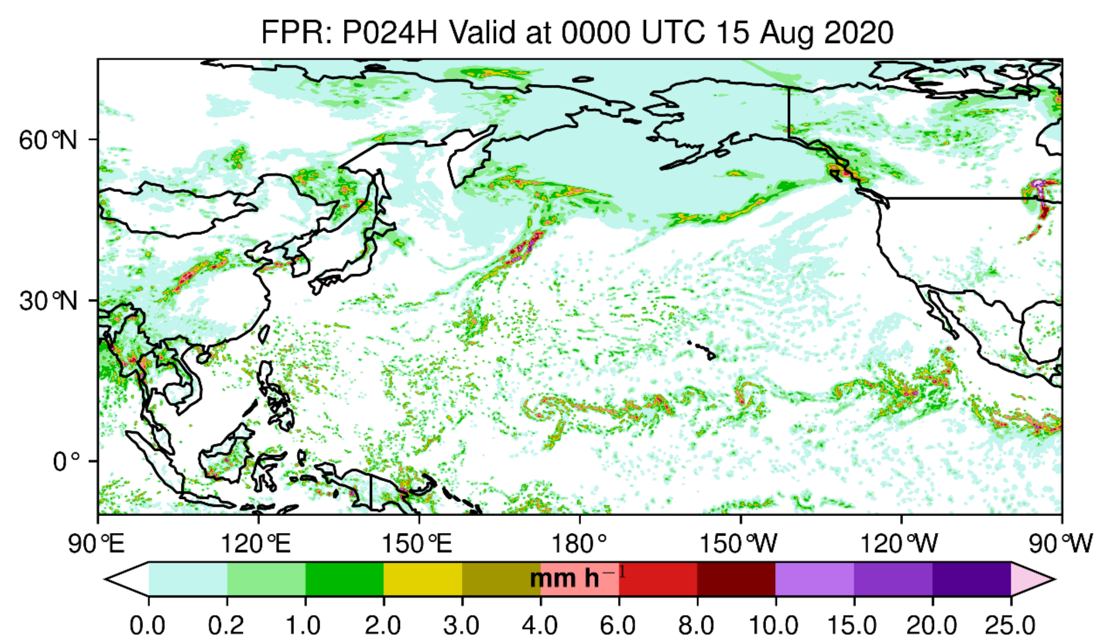

Fig. 4: Forecast precipitation rate (FPR) with a 24-h lead time valid at 0000 UTC 15 August 2020.

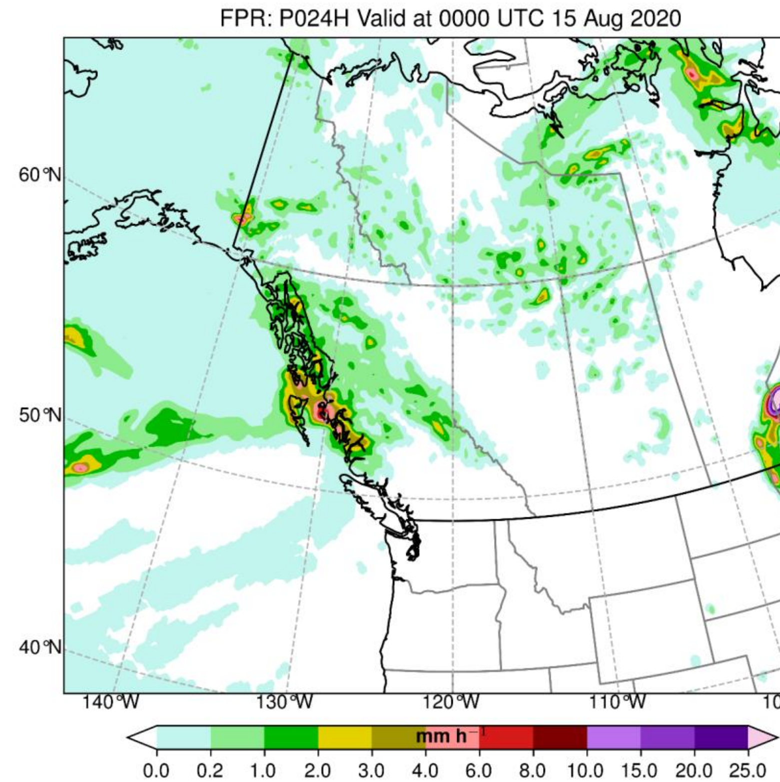

Fig. 5: Same as Fig. 4, except for smaller domain focusing on western Canada.

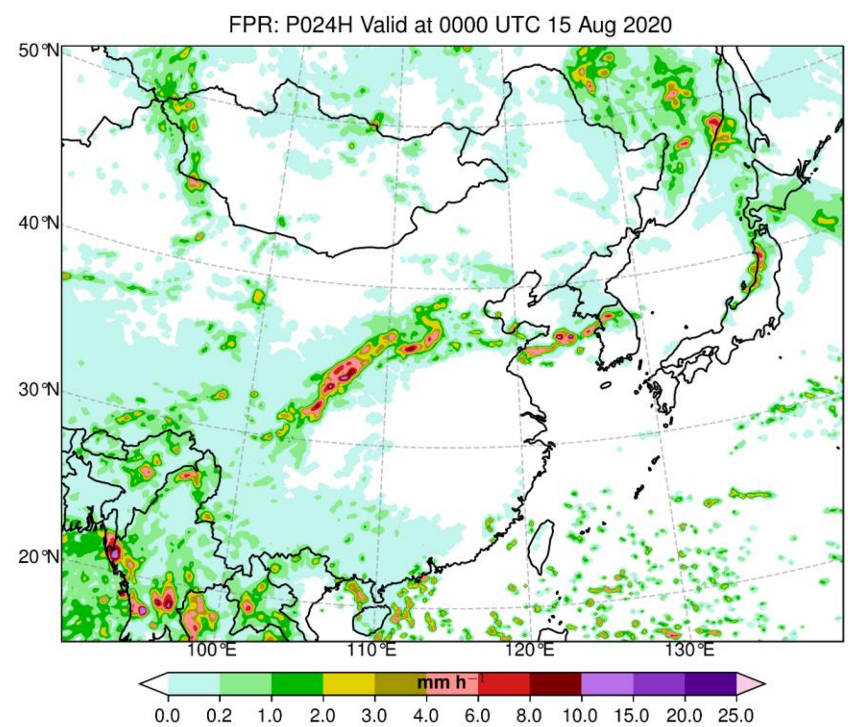

Fig. 6: Same as Fig. 4, except for smaller domain focusing on East Asia.

An optimal value of $\Re_c$ in Eq. (9) can be obtained by calculating C_{rp} based on predicted $\nabla \cdot \mathbf{Q}$ with $\Re_c$ varying from 0 to 1. Comparing these predicted C_{rp} values with the predicted precipitation rates gives the optimal $\Re_c$ that results in the least mean squared error (global average).

Fig. 7 shows the root mean squared error (RMSE) as a function of $\Re_c$ for the 24-hour forecast valid at 0000 UTC 15 August 2020. The optimal $\Re_c$ value for this case is 0.67. Also plotted in Fig. 7 are the optimal $\Re_c$ of the 24-hour forecasts of the 0000 and 1200 UTC model runs of each day from 1 November 2019 to 31 October 2020. These one-year optimal values vary from 0.61 to 0.70, and have an averaged value of 0.659. Based on this result, we can assume that $\Re_c$ = 0.66 is the optimal choice for $n = 1$.

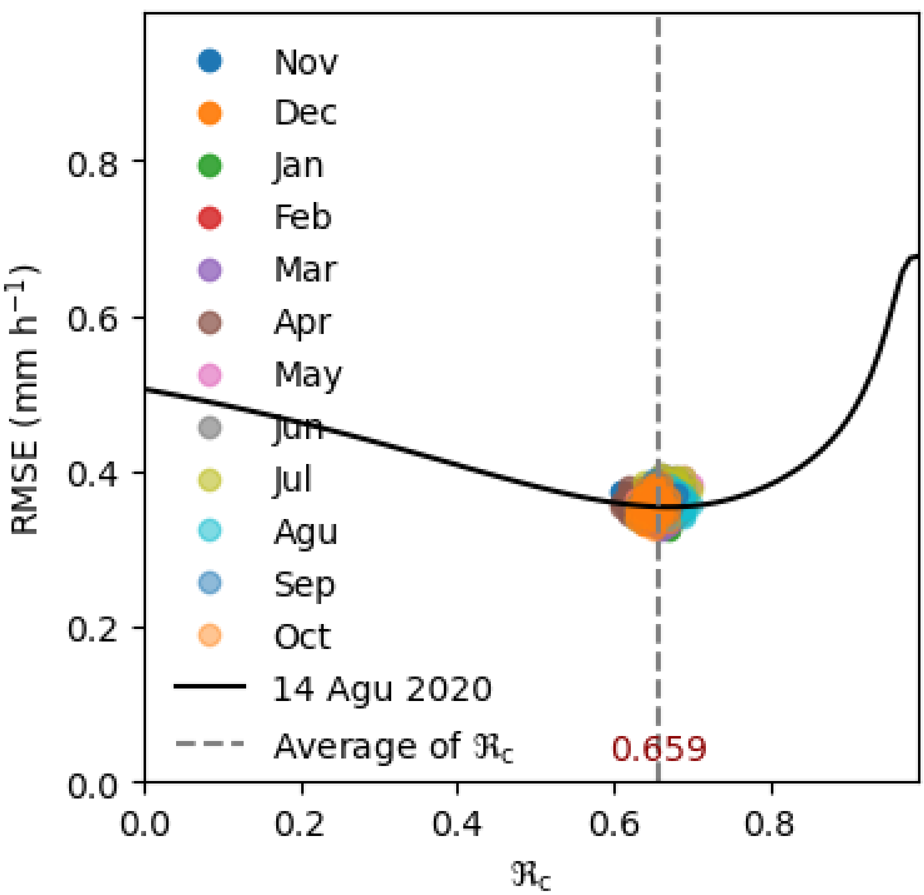

Fig. 7: Optimal $\Re_c$ based on 1-yr 24-h prediction data. See the detailed explanation in the text above.

Figs. 8 and 9 show the 24-h forecast PCR with $\Re_c$ = 0.66. They compare well to the FPR in Figs. 5 and 6 in the areas with heavy precipitation. The PCR diagnosed from the analysis at 0000 UTC 15 August are shown in Figs. 10 and 11.

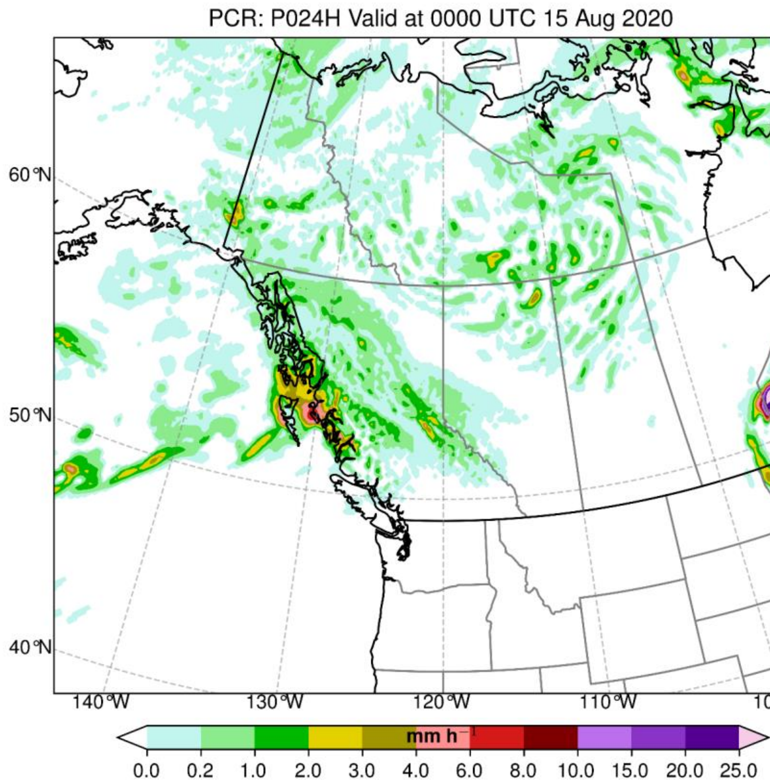

Fig. 8: The PCR in western Canada based on the 24-h forecast fields valid at 0000 UTC 15 August 2020.

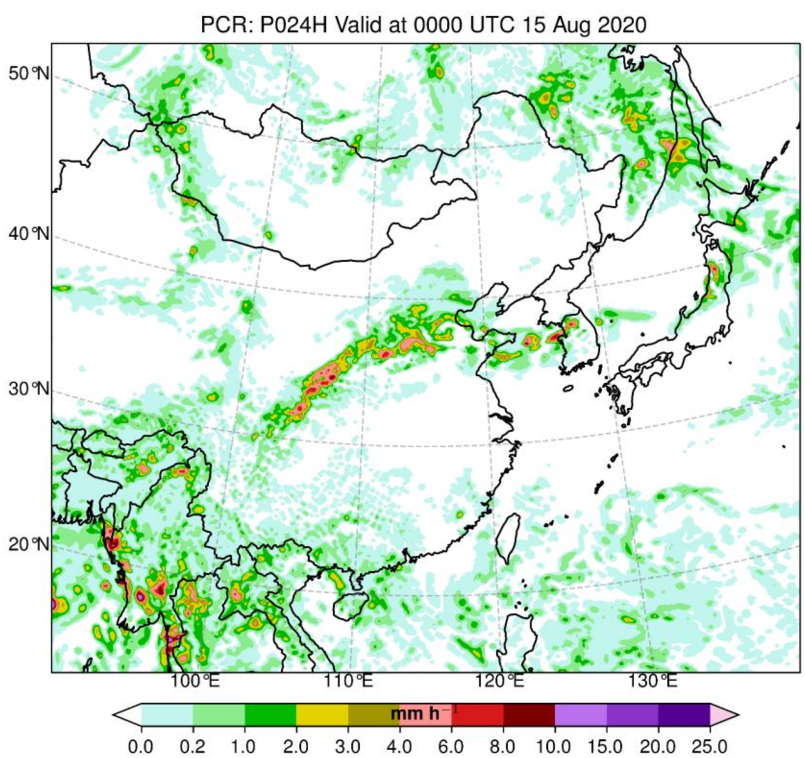

Fig. 9: The PCR in East Asia based on the 24-h forecast fields valid at 0000 UTC 15 August 2020.

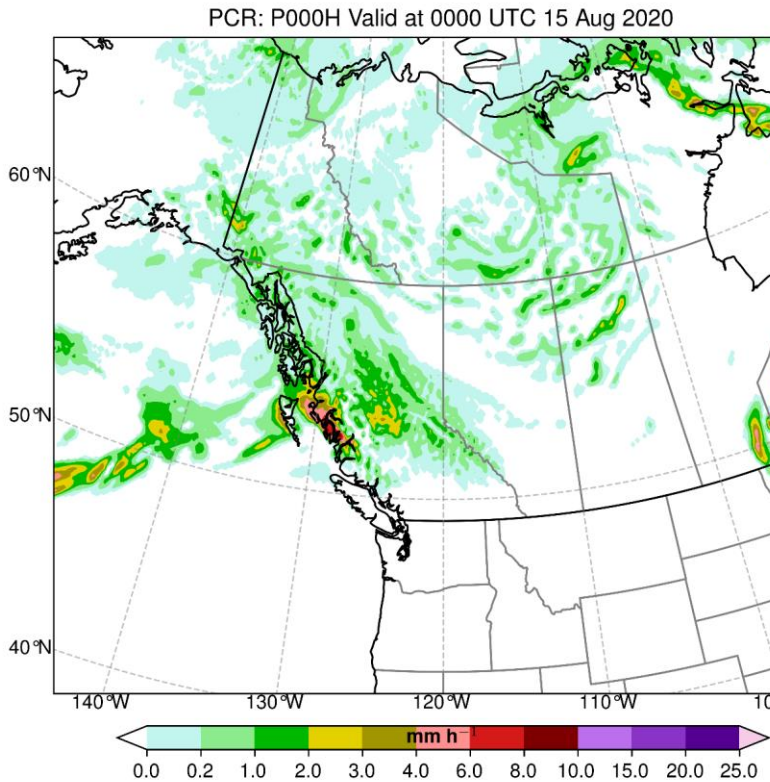

Fig. 10: The PCR in western Canada based on the GDPS analysis at 0000 UTC 15 August 2020.

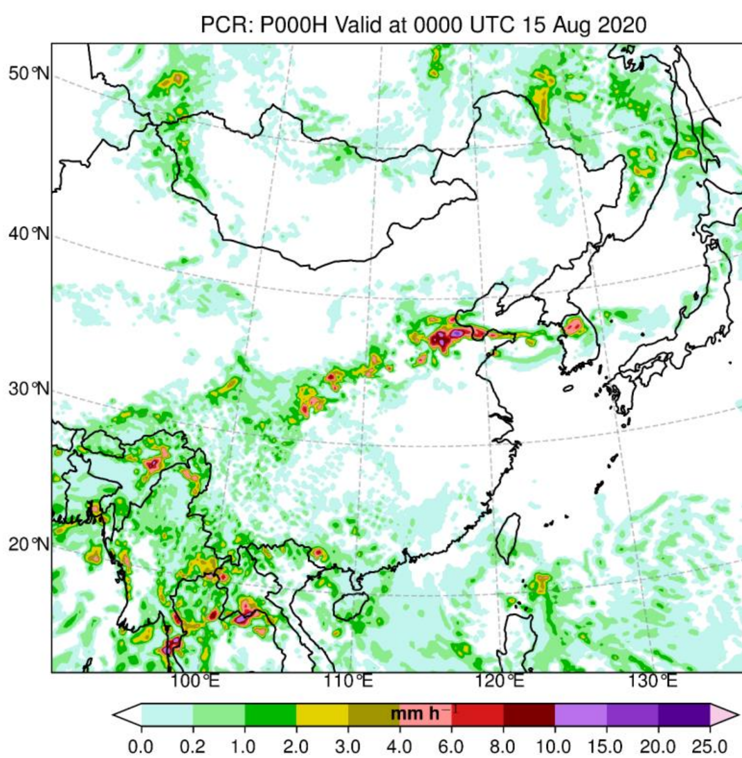

Fig. 11: The PCR in East Asia based on the GDPS analysis at 0000 UTC 15 August 2020.

5. Conclusions

- The column relative humidity (CRH) and the primary condensation rate (PCR) are two useful complementary measures to facilitate atmospheric river (AR) analysis.
- Both CRH and PCR are diagnosable variables. The CRH measures the relative moistness of the air column, and the PCR measures the potential contribution of AR to heavy precipitation.
- The PCR is given as a simple function of the CRH and the convergence of integrated horizontal water vapor flux. It is shown that the PCR with CRH < 0.60 is negligible, and the best cut-off value of CRH for the PCR algorithm is 0.66.
- The diagnosable PCR can be considered as an attribute of the AR system. It can be used to develop an impact-based storm classification system, which can be compared and combined with a strength-based AR classification system (e.g., Ralph et al., 2019).

Selected References

- Amer. Meteor. Soc., cited 2020: Atmospheric river. *Glossary of Meteorology*. [http://glossary.ametsoc.org/wiki/Atmospheric_river].
- Anthes, R. A., 1977: A cumulus parameterization scheme utilizing a one-dimensional cloud model. *Mon. Wea. Rev.*, **105**, 270–286.
- Bretherton, C., Peters, M. E., and Back, L. E., 2004: Relationships between water vapor path and precipitation over the tropical oceans. *J. Climate*, **17**, 1517–1528.
- Kuo, H. L., 1974: Further studies of parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.*, **31**, 1232–1240.
- McTaggart-Cowan, R., and Coauthors, 2019: Modernization of atmospheric physics parameterization in Canadian NWP. *J. Adv. Model. Earth Sys.*, **11**, 3593–3635.
- Peixoto, J. P., 1973: Atmospheric vapour flux computations for hydrological purposes. *Reports on WMO/IHD Projects*, Rep. No. 20, 83 pp.
- Ralph, F. M., and Coauthors, 2019: A scale to characterize the strength and impacts of atmospheric rivers. *Bull. Amer. Meteor. Soc.*, **100**, 269–289.

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