Rossby wave-breaking and moisture transport into the Arctic

Elizabeth A. Barnes & **Chengji Liu** Colorado State University

CMMAP Team Meeting **August 6, 2014** CMMAP Team Meeting

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Rossby waves: undulations in the jet-streams

The Polar Jet Stream NASA Scientific Visualization Studio

Polvani & Esler (2007) **stratospheric tracer**

- midlatitude Rossby waves often propagate on the jetstreams
- they often overturn, or "break"
	- clockwise = anticyclonic wave breaking
	- counter-clockwise = cyclonic wave breaking
- wave breaking is important for momentum fluxes and maintaining the jet-stream
- it may also play a role in transport

RWB occurs on the flanks of the jets

- the momentum fluxes due to RWB largely maintain the midlatitude jet stream
- the jet-stream also modifies the RWB frequencies through its vorticity gradient, speed and position

 \blacksquare form a tightly coupled breaking compared to the other two curves system $\frac{1}{\sqrt{2}}$ \blacksquare $\mathbb B$ and Hartmann, 2012]. The finding minic those findings minic those findings minicipal minic those findings minicipal minicipa \mathcal{L} Hitchmann and Huesmann \mathcal{L} was also found in regions of cross-equations of cross-equations of cross-equations of cross-equations of crossflow. Equatorial westerlies are absent in the lower-RWB and the jet-streams

waves to propagate from one hemisphere to another to another to another to another to another to another to an [Webster and Holton, 1982; Waugh and Polvani, 2000;

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Barnes & Hartmann (2012)

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 $\begin{array}{c} \hline \text{[1]} \text{[1]} \text{[1]} \end{array}$ $\begin{array}{c} \hline \text{[2]} \text{[2]} \end{array}$ is stropped form a tightly coupled RWB and the jet-streams

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Barnes & Hartmann (2012) with the servery servery fluid gray Barnes & Hartmann (2012)

RWB and actual weather: *wind storms*

- evolution of extreme wind-storms over Europe linked to RWB that occur during +NAO events areas where the surface wind exceeds are the surface wind exceeds the surface
- the most intense storms are associated with the simultaneous occurrence of both cyclonic and anticyclonic flavors **compared to the entity of the entity of the entity** of the entity of t the 250 hPa wind (the longest arrow is approximately 50 m s"¹ Figure 2. Evolution of the extreme storm in both the Surface Surface of the 2-PVU surface on the

Hanley & Cabellero (2012)

Atmospheric rivers and RWB

a static image of an AR, as in Figs. 1 and 2, suggests that α

- Atmospheric rivers bring intense precipitation to the west coast of the U.S.
- Many previous studies have suggested a role for the large-scale circulation in this transport extreme produced extreme produced extreme produced extreme produced extreme produced extreme produce α circle spatial coast, and exhibited spatial continuous continu

summary), and (c) eastern Pacific on the morning of 9 Jan 2005. The images were generated using the algorithm of Wentz (1995).

Impact of Rossby Wave Breaking on U.S. West Coast Winter Precipitation during ENSO Events ROSSDY WAVE Breaking on U.S. West Coast Winter Precipitation during circulation cyclonic contents, respectively. The mean of mean of mean α

JU-MEE RYOO,* YOHAI KASPI,⁺ DARRYN W. WAUGH,[#] GEORGE N. KILADIS,[@]
DUALE B. WALEER & FRIGH FETTER ** AND JRWON KN⁺⁺ DUANE E. WALISER, $^{\&}$ ERIC J. FETZER, $**$ AND JINWON KIM⁺⁺

the west coast of the United States with a time lag of 0–1 days. Vertically integrated water vapor fluxes during

 $\text{Correlation} = \text{O}.r$ $\text{conv}_{\text{total}} = \text{V}$.

Ryoo et al. (2013) \mathcal{L} is a high correlation (\mathcal{L} at 250 hPa and precipitation over \mathcal{L} of this tropical water vapor before reaching the coast. 2004), which is consistent with the tensor subsident with the tensor subsident with the tensor subsidence α

Why do we care about water vapor in the Arctic?

- Arctic is warming rapidly compared to the rest of the globe ("Arctic amplification")
- surface energy budget of the Arctic is key in determining its temperature
- water vapor plays a critical role in the surface energy balance

Temperature trends (1989-2008)

 $\mathcal{L}(\mathcal{D})$, spring (March–May; b), spring (May; b), summer (June–August; b), summer (June–Au

from projections of the temperature field on the sea ice time series (Methods

Intense moisture intrusions can change LW fluxes ense moisture intrusions ca chango I W fluvos without the component in Figure 3 (green in Figure 3 \pm

- Intense, filamentary moisture intrusions into the Arctic can modulate the long-wave radiation reaching the surface $\overline{\text{m}}$ dec, mand the many motorup. radiation increased again due to the second pulse of moist moddiate the long wave.
radiation reaching the surface

from the beginning of the measurement are presented to minimize any bias due to local temperature uncertainty and

9 February, which is associated with the maximum of WV

 $\overline{3.0}$

western Canadian Arctic Arctic Arctic Arctic Arctic Archipelago and Beaufort Sea was a structured with Sea was
Beaufort Sea was a structured with Sea was a structured with Sea was a structured with Sea was a structured wi mostly dry, with moist air over mainland North America.

tions (black line), with most of the fluctuations due to clouds due to clouds due to clouds due to clouds due to c

Figure 1), with motions (PW $\frac{1}{2}$ mm; reduced by $\frac{1}{2}$ mm; redu regions), incoming from lower latitudes. On 6 February, the longwave irradiance (grey line). Temporal variation in the *adapted from Figure 1* t_1 / (2212) $\left[1\right]$ and $\left[1\right]$ figure 3 shows the simulated change in downwelling in downwell *Woods et al. (2013)*

irradiance during the intrusion of 17 W m−² was simulated, which is in agreement with the pyrger measurement with the pyrgeometer measurement. The pyrgeometer measuremen

Figure 1. Panel Marchiot of Public mosaic of Public mosaic mosaic of Public mosaic mosaic mosaic mosaic mosaic
The Microwave Humidity (NOAA) based Microwave Humidity Microwave Humidity Microwave Humidity Microwave Humidit downwelling $S \sim 2$ February, $2\sqrt{3}$ is matter with N for N and N and R long-wave radiation 06 12 18 $00\,$ 06 18 00 $00\,$ 12 06 ¹² $F_{\text{eff}}\rightarrow 0$ $\begin{array}{c} \begin{array}{c} \begin{array}{c} \text{S} \end{array} \\ \text{S} \end{array} \end{array} \end{array}$ $\begin{bmatrix} 1 & A & B & C \end{bmatrix}$ of $\begin{bmatrix} 1 & A & A & B \end{bmatrix}$ based Microwave Humidity (NOA) $\widehat{C_1}$ $\widehat{50}$ $$ $\$ $\begin{array}{ccc} \uparrow & 50 \\ \uparrow & 50 \end{array}$ and $\begin{array}{ccc} \uparrow & \downarrow & \downarrow \\ \downarrow & \downarrow & \downarrow \end{array}$ $\sum_{n=1}^{\infty}$ so $\sum_{n=1}^{\infty}$ so $\sum_{n=1}^{\infty}$ so $\sum_{n=1}^{\infty}$ so $\sum_{n=1}^{\infty}$ so $\sum_{n=1}^{\infty}$ $\begin{bmatrix} 1 & 30 \\ 2 & 0 \end{bmatrix}$ $\begin{bmatrix} 2 & 30 \\ 2 & 0 \end{bmatrix}$ $\begin{bmatrix} 2 & 30 \\ 2 & 0 \end{bmatrix}$ $\begin{bmatrix} 2 & 30 \\ 2 & 0 \end{bmatrix}$ $\begin{array}{c}\n\text{E} \\
\text{E}\n\end{array}$ $\begin{array}{c}\n\text{Fyrgometer} \\
\text{Simulation}\n\end{array}$ $\begin{array}{c|c}\n\hline\n\vdots \\
\hline\n\end{array}$ between $\begin{array}{c|c}\n\hline\n\vdots \\
\hline\n\end{array}$ between $\begin{array}{c|c}\n\hline\n\vdots \\
\hline\n\end{array}$ $\begin{bmatrix} 1 & 2 & 3 \ 2 & 40 & 2 \end{bmatrix}$ for details. See Section 2.1 for details. $\begin{bmatrix} 6 & 40 \\ 8 & 1 \end{bmatrix}$ between 16:00 and 22:00 utch missing data above missing data above missing data above missing data above $\begin{bmatrix} 1 & 1 \\ 0 & -1 \end{bmatrix}$ $\frac{1}{2}$ 30 $\frac{1}{2}$ 1 km is the coast $\frac{1}{2}$ and $\frac{1}{2}$ \mathbb{E} temperature in \mathbb{E} and \mathbb{E} and \mathbb{E} and \mathbb{E} and \mathbb{E} and \mathbb{E} \mathbb{R} \mathbb{R} \mathbb{R} and \mathbb{R} was array towards \mathbb{R} was an \mathbb{R} was an \mathbb{R} was an \mathbb{R} was array towards \mathbb{R} was array towards \mathbb{R} was array towards \mathbb{R} was an \mathbb{R} was array $M_{\rm max}$ moisture north of the Canadian Arctic coast at 700 hPa. One coast at 700 hPa. On $120 - 100$ $\frac{1}{20}$ 20 hPa and $\frac{1}{20}$ moving $\frac{1}{20}$ $\begin{bmatrix} 8 & 1 \end{bmatrix}$ $\begin{bmatrix} 8 & 1 \end{bmatrix}$ $\begin{bmatrix} 1 & 1 \end{bmatrix}$ $\frac{1}{\sqrt{2}}$ for $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$ disrupted by a subsequently developed by a subsequently \mathcal{L} $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ $\overline{\hspace{1em}}$ θ 2.2. Microwave Humidity Sounder t_{09} and t_{10} m. Integrating the line line mosaic mosaic mosaic mosaic mosaic mosaic mosaic mosaic neutral t_{11} Date in February 20 p_{av} is the column depth of p_{av} and $p_{\text{$ for 6–9 February 2011. Superior by Doyle et al. (2011) Doyle et al. (2011)

00:00 to 12:00 UTC were combined (usually seven) for each $\frac{1}{2}$ Panel are shown in Figure 1. The shown in Figure 1

L12806 DOYLE ET AL.: WATER VAPOR INTRUSIONS L12806

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Moisture transport into the Arctic

- Total moisture transport into the Arctic:
	- largest in summer
	- smallest in winter
- S ynoptic + Low-Frequend provides almost all of the transport (transients)
- Synoptic transport is an important component of the total transport into the Arctic

Lef anomalies into each region is determined by the vertical average of the vertical average of the vertical α

Newman et al. (2012) α is equal to pair is equal to P 2 E also averaged in each pair α

Moisture transport occurs in bursts

- high-latitude moisture transport often occurs as high-intensity plumes
- 6-hourly transport has a very large tail (skewed toward positive extremes)

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similar conclusions reached by others e.g. Woods & Caballero (2013), Doyle et al. (2011)

Vonder Haar et al. (2012)

Extreme transport is important in total budget

Extreme moisture transport (90th %tile of fluxes) (a) DJF

- Extreme transport accounts for more than 60% of total transient poleward moisture transport (v'q')
- Across 60N, extremes account for…
	- 69% in winter
	- 66% in summer

upper-level flow, depicted here by the potential temperature by the potential temperature by the potential tempera-

Large-scale circulation associated with moisture intrusions into the Arctic during winter

Cian Woods,¹ Rodrigo Caballero,¹ and Gunilla Svensson¹

Potential temperature on 2PVU

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tion is low or absent and the atmospheric boundary layer layer layer layer layer layer layer layer layer layer

so that the surface energy budget is almost entirely gov-

 $\left(3, 1, 2, 3, 4, 6\right)$ *Woods et al. (2013)*

we present in Figure 1 a specific example of the type of the type

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across the Labrador Sea the state associated associated associated associated associated and the state and the state and the state and the state associated associated associated associated associated and the state and the state and the state and

 $e^{i\omega t}$ Cyclonic wave breaking! begins in the early hours of 1 January 1998 (this is the

60◦N. (c) The same as (a), but for poleward moisture transport across 180◦W∼170◦W at 60◦N

Liu & Barnes (in prep)

CSU Elizabeth A. Barnes D R A F T JULY 30, 2014, 10:18:19 A F T T JULY 30, 2014, 10:18:18.

Composites of potential temperature on 2PVU during extreme poleward moisture transport events

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The goal of this work is to quantify the contribution of RWB to moisture transport into the polar cap.

Liu & Barnes (in prep) moisture transport associated with RWB in the algorithm. Bottom: Composite poleward moisture transport

1. identify RWB by searching for overturning of potential temperature on the 2PVU surface Liu et al. (2014)

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- 4. find RWB contours that overlap intense "blobs" of v'q'

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Sanity check

Composites of potential temperature on 2PVU during poleward moisture transport events

Anticyclonic wave breaking

Cyclonic wave breaking

Sanity check α

Composites of potential temperature on 2PVU during poleward moisture transport events

Composites of poleward moisture transport on wave breaking events

relative longitude

Liu & Barnes (in prep) Figure 4. Upper: Snapshots of polential models of polential models of polential models and those associated with $\frac{1}{2}$

Contribution of RWB to transport

- RWB contribution occurs along the storm tracks
- RWB accounts for a large fraction of extreme transient poleward moisture transport across 60N
	- **68%** in winter
	- **56%** in summer
- Of the total transient transport across 60N, RWB accounts for more than
	- 47% in winter
	- 37% in summer

Extreme moisture transport in DJF

(a) Total transport

(b) RWB transport

Cyclonic vs Anticyclonic

- Cyclonic breaking has a larger contribution at higher latitudes (on the cyclonic flank δ of the jet). (c) The same as (b), but for anticipation δ and δ the same as (b), but for anticipation δ $\mathcal{L}(\mathcal{C})$, but for anticipation $\mathcal{C}(\mathcal{C})$ and $\mathcal{C}(\mathcal{C})$ but for cyclonic $\mathcal{C}(\mathcal{C})$ $\frac{1}{\sqrt{2}}$ Ω valence hyperliner heep a love as entripy tien of higher Ω
- Anticyclonic breaking contributes more overall than cyclonic RWB (CWB) only. D R A F T July 30, 2014, 10:18am D R A F T \mathcal{L}

Contribution of Anticyclonic RWB in midlatitudes

40˚N

(c) AWB transport

- Hot-off-the-press results by Payne & Magnusdottir:
- role of anticyclonic wave breaking in extreme moisture **Figure 1. (a)** Climatological winter moisture transport. (b) climatransport to the western US

jet stream (200 hPa wind speed) $\mathcal{L}_{\mathcal{B}}(\mathcal{B})$ the same as (b), but for anticipation $\mathcal{B}(\mathcal{B})$ only. (d) $\mathcal{B}(\mathcal{B})$ but for cyclonic $\mathcal{B}(\mathcal{B})$

> Payne & Magnusdottir (2014) is magnetered by a filled red dominated red download to the set of the set of the set of the set of the set of
Flizabeth A Ran

- What determines the seasonal cycle of RWB contribution?
	- **Magnitude:** are we getting more moisture flux per RWB?
	- **Frequency:** is RWB becoming more frequent?

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TOTAL moisture transport due to RWB = **(M)** Magnitude of moisture per event x **(F)** Frequency of RWB

$$
(MF)' = M' \overline{F} + \overline{M}F' + \text{other terms}
$$

- seasonality of the RWB-related transient transport is due to
	- (a) amount of moisture flux
- \cdot (b) frequency of RWB
- frequency of RWB is tightly coupled to the jet position (the black line over North Atlantic in Figure 5c). Black dashed line: Approximation for black solid

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Year-to-year variability: NAO

- RWB is tightly-tied to the lowfrequency variability of the jetstreams
- Some studies suggest that in fact they are one and the same!
- Also, the type of RWB and location can be important in driving jet-variability Benedict et al. (2004), Strong & Magnusdottir (2008)

Cyclonic Greenland wave breaking correlated with the NAO

Benedict et al. (2004)

Year-to-year variability: NAO

- NAO modulates RWB-moisture transport across 60N
	- decrease over Greenland
	- increase over UK & **Scandinavia**
- Pattern is a well-known response of RWB to the NAO

Liu & Barnes (in prep) Figure 9. (a) Regression of wintertime monthly poleward moisture transport associated with Rossby

Year-to-year variability: ENSO

- During El Nino events, jet shifts equatorward
- More cyclonic RWB
- Less anticyclonic RWB

Ryoo et al. (2013)

Year-to-year variability: ENSO

- ENSO modulates RWB-moisture transport across 60N
	- decrease over North Pacific
	- increase over western Canada
	- overall decrease across 60N
- both flavors of RWB contribute to these changes

One more thing…models have difficulties with the jet

- models place the jet too far equatorward
	- models tend to over-estimate the seasonal cycle of the jet

 \sim 1 simulate moisture into the Arctic implications for how models

The Future: jet shifts ano. Joi ornito

- CMIP5 models project poleward shifts of the jet-stream in most seasons and Blackburn (2012) for CMIP3 and Blackburn (2012) for CMIP3 and Blackburn (2013) for CMI of the jet exit and a weakened zonal wind much farther wind its or the Jet-Stream in most

a consensus on a strengthened westerly wind at the jet α

Atlantic jet in a basin-mean analysis across the Atlantic

SON, DJF, MAM, and JJA seasons are shown in Figs. 9, 10, 11, and 12, respectively. The t^u responses of the 13-

- zonal differences in the North Pacific jet response in winter $T_{\rm H}$ shift of the Atlantic and Pacific jets as a function $T_{\rm H}$ of longitude and day of the year is summer

Barnes & Polvani (2013)

this range.

subtropical jet has a seasonal cycle, maximizing in the

one might expect the North Pacific summertime [June–

Simpson et al. (2014) J_{III} psointstal.

The Future: jet shifts & RVB

(Figures 8c and 8d), perhaps due to the model \mathcal{S}

- future poleward jet shifts are tied to changes in the distribution c RWB

sphere wave breaking events at 250 hPa per year per degree

is not as clear. In addition, anticyclonic wave breaking events

The Future: jet shifts & RVB

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poleward jet-stream = fewer cyclonic RWB

Barnes & Polvani (2013) **Fig. 10. Zonally integrated wave-breaking frequency profiles for the frequency profiles for** α **,(d),(d),(d),(d),(h) cyclonic wave breaking (AWB) and (b),(h) cyclonic wave breaking (AWB) and (b),(h**

- More poleward jets are linked to less cyclonic RWB denoted along the x axis. The thick line denotes the 1:1 line and thus the position of the mean jet. (c),(f),(i) Cyclonic wave-breaking

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If the jet shifts poleward in the future, will we have less cyclonic RWB-induced moisture transport at 60N?

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If the jet shifts poleward in the future, will we have less cyclonic RWB-induced moisture transport at 60N?

We don't know yet!

(but changes in the moisture capacity of the atmosphere will likely dominate)

clockwise rotation would be termed the term of the

 $\frac{1}{2}$

Conclusions

- 1. Extreme synoptic moisture transport events contribute a substantial amount to the total transient moisture transport across 60N
- 2. Synoptic Rossby waves are an important driver of these extreme intrusion events

3. Future changes in the jet-stream and Rossby wave breaking frequency have the potential to drive changes in the intensity and frequency of these intrusions

