Prediction of Atmospheric Rivers in NMME
Progress Report (Final Report)

1. General Information

Project Title: Prediction of Atmospheric Rivers in NMME
PI/co-PI names and institutions: Hyemi Kim (Stony Brook University)
Report Year: 08/01/2015 - 07/31/2017
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2. Main goals of the project, as outlined in the funded proposal

The goal of the proposed research is to assess the ability of Atmospheric Rivers (ARs) prediction in climate models from month to season. The main steps of the proposed work are:

- Investigate the source of AR predictability by understanding the processes related to ENSO
- Assess the AR characteristics (frequency, duration) in NMME
- Evaluate the prediction skill of ARs for months to seasons
- Evaluate models capability in representing ENSO-ARs processes.

3. Results and accomplishments

I. Additional results to the 1st Progress Report.

<u>(a) Investigating the source of AR predictability in the North Atlantic (Task 2 of proposal)</u>
The interannual variability of wintertime ARs over the North Atlantic is examined with daily column-integrated moisture flux. With explaining more than 30% of the total variance, the first EOF mode of AR frequency over the North Atlantic indicates that the interannual variability of wintertime AR frequency is strongly influenced by the fluctuation of North Atlantic Oscillation (NAO), but not the ENSO. A seesaw pattern of ARs appears over the western Europe in the fluctuation of two NAO phases, where a positive NAO phase corresponds to a poleward shifted subtropical jet, and mid-latitude anomalous anticyclonic flow induced by the intensified Azores High. During Positive NAO, more moisture transport occurs in the northwestern Europe, and more landfalling ARs locate north to 50°N.

<u>(b) Assessing NMME seasonal prediction skill of North Atlantic ARs (Task 1 of proposal)</u>
The NMME seasonal predictions of winter (DJF) ARs and moisture transport in response to NAO are evaluated. Predictions of the average of one to three months lead (initialized in early November) are examined with five NMME hindcast models. Models show modest prediction skill of NAO. The vast spread of performance of ensembles in models implies that prediction of

NAO is strongly limited to synoptic features and internal variability of the atmosphere, which indicates that the models fail to capture the low-frequency year-to-year variance of NAO (Fig.1). Therefore, the seasonally prediction of winter NAO and ARs remains challenging.

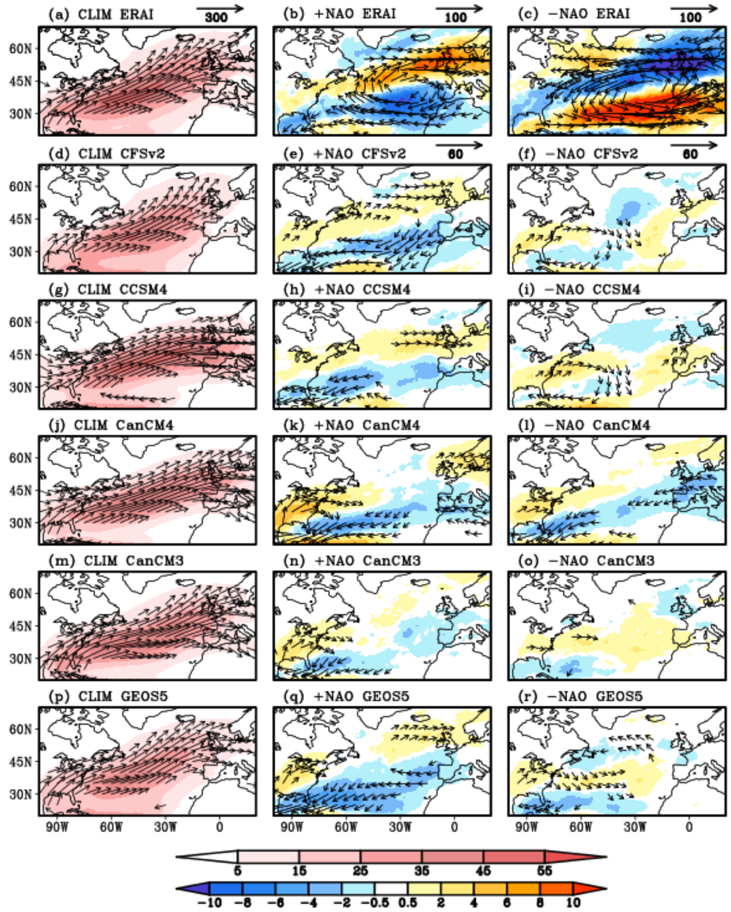

Fig. 1: AR frequency (shadings, days per winter) and vertically-integrated moisture flux (vectors; (left) shows values exceed 70 kg m^{-1} s^{-2}; (b-c) shows values that exceed 30 kg m^{-1} s^{-2}; the rest shows values that exceed 10 kg m^{-1} s^{-2}) for (left) climatology, (middle) +NAO anomaly, and (right) -NAO anomaly.

II. 1st Progress Report (submitted in May 2016).

(a) Investigating the source of AR predictability (Task 2 of proposal)

The PI has investigated the year-to-year changes in ARs and moisture transport over the northeast Pacific and western North America during Northern Hemisphere winter from 1979/80 to 2015/16. Changes in ARs frequency, intensity, and landfall characteristics are compared between three ENSO phases: central Pacific El Niño (CPEN), eastern Pacific El Niño (EPEN), and La Niña (NINA). During EPEN events, the subtropical jet extends to the south and east with an anomalous cyclonic flow around a deeper Aleutian Low. More moisture is transported towards North America and AR frequency is increased over western North America (Fig. 1d). In CPEN events, the Aleutian low shifts further southward relative to its position in EPEN, resulting in an increase in the frequency and intensity of landfalling ARs over the southwestern US. In NINA events, the landfalling AR frequency is reduced associated with anomalous anticyclonic circulation over the eastern North Pacific (Fig.1).

We diagnose the contribution of multiple factors to the seasonal mean moisture transport (thus ARs) using moisture budgets (Fig.2) During the three ENSO phases, the change in low-frequency circulation (dynamical process) is the leading contributor to the seasonal mean moisture flux divergence, while the contributions of the synoptic anomalies and the change in moisture anomaly (thermodynamic process) are not significant along the west coast of North America.

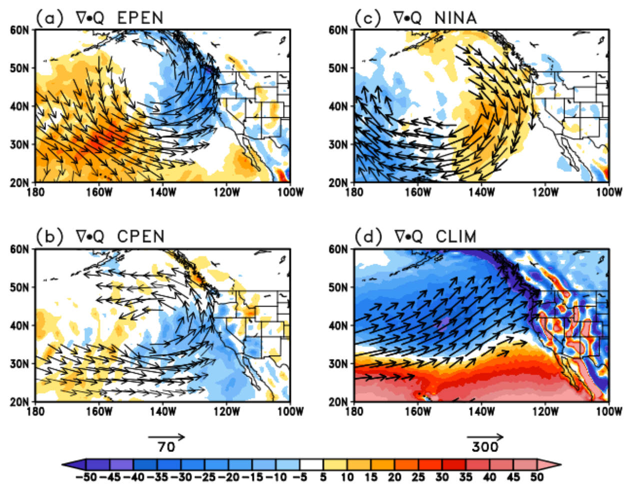

Figure 1. The vertically integrated seasonal moisture flux divergence (shading, 10-6 kg m-2 s-1) for (d) climatology and anomalies for (a) EPEN, (b) CPEN, and (c) NINA. The vectors have exceeded the 95% significant level based on a bootstrap method. (Kim et al. 2017)

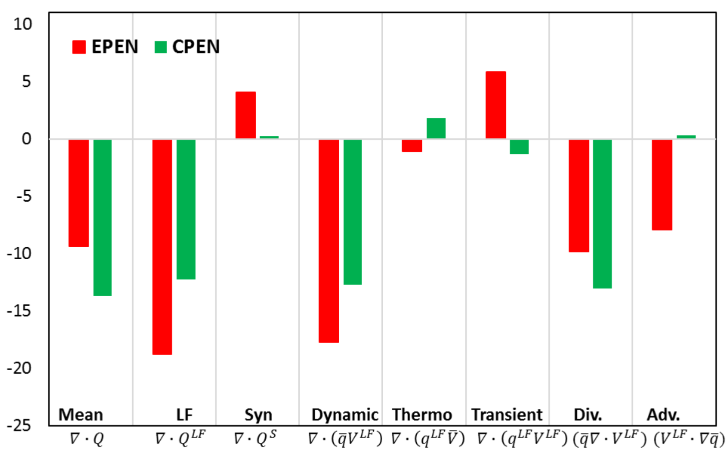

Figure 2. Anomalies of moisture flux divergence (10^{-6} kg m^{-2} s^{-1}) for seasonal mean, low-frequency (LF) and synoptic (Syn) terms, low-frequency dynamic, thermodynamic. transient, mass-divergence, and advection terms for EPEN (red) and CPEN (green) averaged along the US west coast. (Kim et al. 2017)

b) Assessing monthly to seasonal prediction skill of ARs (Task 1 of proposal)

The linkage between ENSO and ARs presents a potential source of seasonal AR prediction and associated extreme events, although the assessments of the seasonal prediction of ARs and moisture transport have never been attempted. We investigated how well the state-of-the-art climate models predict the year-to-year change of the seasonal mean AR activity and moisture transport in association with ENSO, using reforecasts from the North American Multi-Model Ensemble (NMME) system including the CFSv2, CCSM4, CanCM3, CanCM4, GEOS5, and GFDL CM2.1. The prediction skill is estimated for the active AR season, December-February (DJF), using NMME hindcasts initialized around early November. Models underestimate the climatological moisture flux to different extents corresponding with various systematic biases in predictions of sea surface temperature (SST) and large-scale atmospheric circulation fields (Fig. 3).

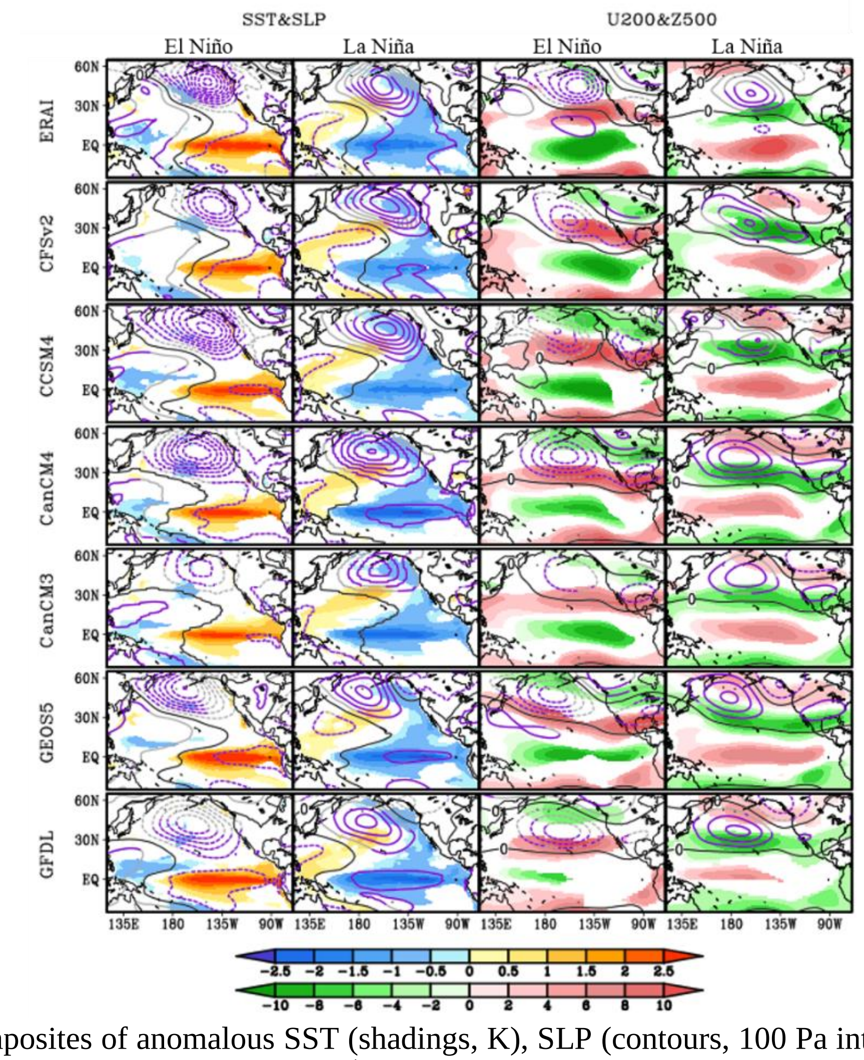

Figure 3. Composites of anomalous SST (shadings, K), SLP (contours, 100 Pa interval), 200 hPa zonal wind (U200, shadings, m s^{-1}), and 500hPa geopotential height (Z500, contours, 20 m interval) for El Niño and La Niña in ERAI and NMME models. Shadings and purple contours show the values that have passed the 95% significant *t*-test level. (Zhou and Kim, submitted)

Figure 4 (left side) shows the climatology of observed and predicted AR frequency during DJF. The AR frequency in the NMME models represents the average of AR frequencies from individual ensemble members (not the AR frequency from the ensemble mean). Higher AR frequency appears over the Northeast Pacific Ocean in both ERAI and NMME predictions. The distributions of anomalous AR frequency during both ENSO phases are relatively well predicted in CFSv2, CCSM4, and CanCM4. The CanCM3 predicts the anomalous pattern of AR frequency, but the magnitude is only 50% of the ERAI.

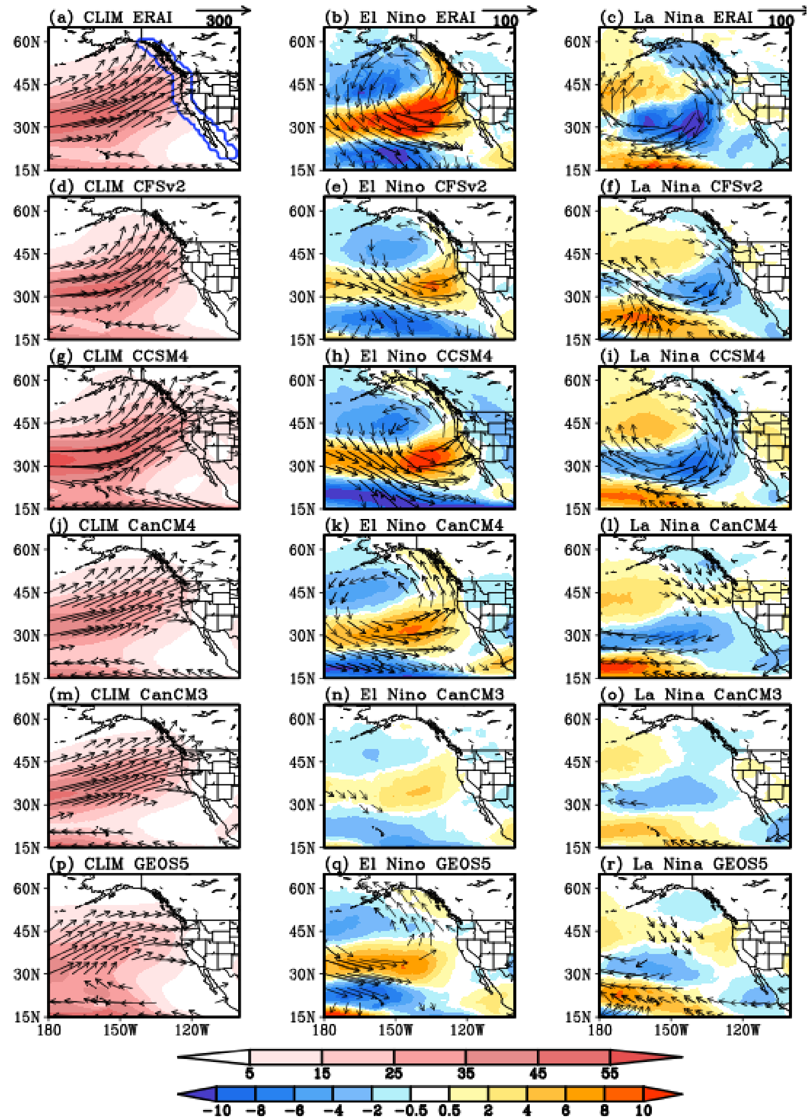

Figure 4. Same as Figure 3, except for AR frequency (days per winter, shadings). (Zhou and Kim, submitted)

The latitudinal distribution of predicted climatology of AR frequency in the Northeast Pacific (180°-120°W) is compared with the ERAI (Fig. 5). In ERAI, large AR frequency (> 30 days) is shown in the midlatitudes between 30°N-40°N. Models roughly capture the distribution of AR frequency, except for GEOS5 in which the AR frequency is underestimated. When the AR frequency is averaged over the Northeast Pacific (Fig. 5a), the peak of the AR frequency is 38.4

days per winter at 36°N in ERAI. The NMME prediction of the peak AR frequency ranges from 30 to 42 and the peak latitude from 34° to 38°N. Latitudinal distributions of observed and predicted landfalling AR frequency are also compared (Fig. 5b). Maximum landfalling AR occurrence in ERAI is around 45°N with about 18 landfalling ARs days per winter. The NMME models predict the climatological distribution of the landfalling ARs to some extent, but with biases in its magnitude and location. CCSM4 overestimates, while CFSv2 and GEOS5 underestimate, the landfalling AR frequency. CanCM3 and CanCM4 show good agreement with the ERAI.

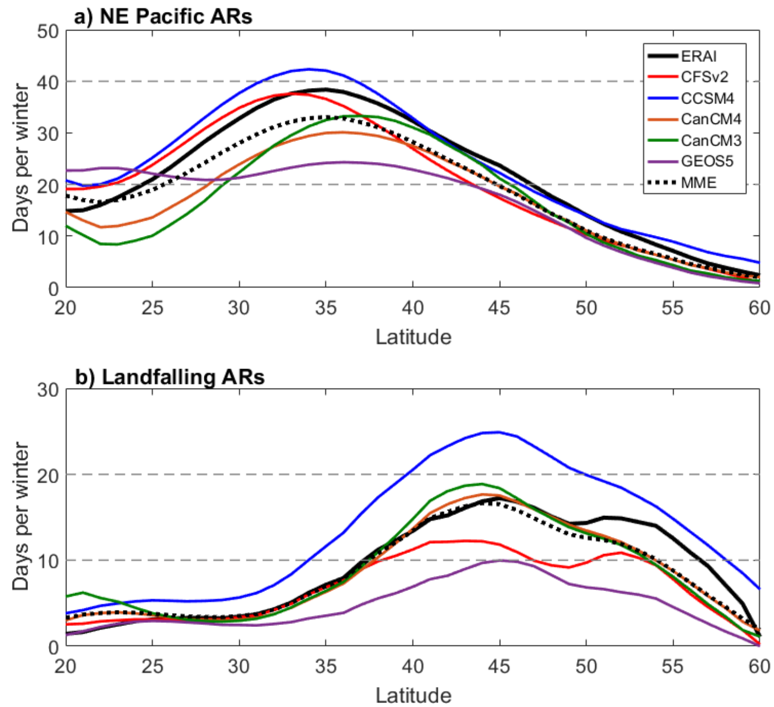

Figure 5. Zonally averaged climatological AR frequency over (a) the Northeast Pacific (180°E-120°W) and (b) the west coast of North America along 20°N-60°N. 5-point smoothing is applied with equal weighting in (b). (Zhou and Kim, submitted)

4. Highlights of Accomplishments

- A collaboration between the PI and collaborators resulted in a paper on how the ENSO modulates Atmospheric River and moisture transport (Kim et al. 2017) that has been accepted for publication in Climate Dynamics.
- Follow-up studies have been conducted that clearly demonstrate how the NMME hindcast can predict the ENSO-AR relationship. Model biases and prediction skill are compared.
- Our assessment of NMME prediction of ARs demonstrates that NMME multi-model ensembles have significant skill in predicting AR activity in the seasonal time scale during ENSO years.
- Result about the NMME seasonal prediction was submitted to Climate Dynamics on March, 2017. It is under review.

- A follow-up study showed that the moisture transport and ARs in the North Atlantic are significantly modulated by the North Atlantic Oscillation (NAO) in both reanalysis and in NMME models. These results will be submitted to JGR-Atmosphere soon.

5. Transitions to Applications

N/A.

6. Publications from the Project

Kim, H. M., Y. Zhou and M. A. Alexander, 2017: Changes in atmospheric rivers and moisture transport over the Northeast Pacific and western North America in response to ENSO diversity, *Climate Dynamics,* DOI: 10.1007/s00382-017-3598-9, in press.

Kim, H. M. and Y. Zhou, 2016: Prediction of Atmospheric Rivers associated with modes of S2S variability, *U.S. CLIVAR Variations.*, Vol.14 (Fall 2016), pages 24-30.

Zhou, Y. and H. M. Kim: Prediction of atmospheric rivers over the North Pacific and its connection to ENSO in the North American Multi-Model Ensembles (NMME), *Climate Dynamics,* submitted.

Zhou, Y. and H. M. Kim: Winter North Atlantic Moisture Transport Corresponding to North Atlantic Oscillation, in preparation.

7. PI Contact Information

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8. Budget for Coming Year

$0.0

9. Future Work

- The study of AR has been extended to subseasonal timescale. The study of the MJO-AR relationship and its predictability is ongoing.