

## Influences of a shift in North Pacific storm tracks on western North American precipitation under global warming

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Recent global climate model simulations for the IPCC Fourth Assessment report show a realistic North Pacific storm track and Aleutian Low for the present-day climate conditions. Under climate change, the storm track and Aleutian Low move northward and intensify. These changes shift precipitation northward along the Pacific coast of North America. In particular, precipitation is intensified over the Pacific Northwest. Results from a statistical downscaling model suggest that precipitation may become more intense both due to the increased frequency of large-scale storms and due to changes in the interaction of these storms with the local terrain.

### 1. Introduction

In a recent study, Yin [2005] describes an intensification and poleward shift of midlatitude storm tracks associated with climate change as simulated in several climate models. This shift, and associated dynamical changes, has profound implications for the climate of the Western United States, which we present in this paper. The most obvious is a northward shift in precipitation due to storms arriving from the North Pacific. A second is the change in the mean pressure field off the coast, which controls a variety of climate impacts including the orographic enhancement of precipitation and coastal ocean processes. Variations of this Aleutian Low and the associated response of the climate in the North Pacific have been extensively studied [Hartmann and Wendler, 2005; Overland *et al.*, 1999; Raible *et al.*, 2005]. Evidence is presented elsewhere for more intense and poleward cyclones in the 20<sup>th</sup> Century [Fyfe, 2003; McCabe *et al.*, 2001] and in scenarios for the 21<sup>st</sup> Century [Kushner *et al.*, 2001]. In a modeling study, Raible and Blender [2004] found that ENSO-like tropical variability in climate simulations could produce changes in the mid-latitude storm tracks. Fu *et al.* [2006] recently showed how satellite-observed mid-tropospheric warming from 1979-2005 implies a poleward shift in the mid-latitude jet stream.

Changes in precipitation for the western U.S. under future climate scenarios are difficult to characterize. 20<sup>th</sup> Century data for the Pacific Northwest, for example, show considerable variability in space and time [Mote, 2003]. Climate model simulations under future emissions scenarios for the 21<sup>st</sup> Century, however, show an aggregate trend for moderate increases in winter precipitation [Mote *et al.*, 2005]. Even such a moderate increase would alter the frequency of extreme events, with important impacts to the region. This paper examines how changes in the Pacific storm track might alter precipitation over western North

America in climate change scenarios. We examine the ability of several climate models to represent the present-day storm track in the Pacific in comparison to reanalysis data. We then examine how these models simulate changes in the storm track for future climate scenarios. Finally, we consider the effect of these changes on the local precipitation patterns in the Pacific Northwest.

### 2. Climate Simulations

For this study, a selection of simulations performed for the International Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) was analyzed. Simulation data are available from the IPCC Data Archive at Lawrence Livermore National Laboratory (<[http://www-pcmdi.llnl.gov/ipcc/about\\_ipcc.php](http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)>). Here we consider as a baseline climate the 1950-2000 simulations for historic conditions. For future climate we consider the 2050-2100 simulations for the IPCC Special Report on Emissions Scenarios [Nakicenovic *et al.*, 2000] A2 emissions scenario (SRES A2). In particular, we shall use the 10 models: HADCM3, ECHAM5, CCSM3, PCM1, CNRM-CM3, CSIRO-MK3 MIROC-3.2, IPSL-CM4, CGCM-3.1, and GISS-ER. For validation purposes, the climate models will be compared to the NCAR-NCEP Reanalysis Project data [Kalnay *et al.*, 1996]. In a comparison of storm tracks represented by various reanalysis projects, Hodges [Hodges *et al.*] has shown the NCAR-NCEP Reanalysis produces similar storm tracks in the lower troposphere to other projects.

### 3. Precipitation

As can be verified from high-frequency data, the mean precipitation pattern for the months November-December-January (NDJ) closely conforms to the storm track as defined by baroclinic activity. Figure 1a shows the 1950-2000 mean NDJ precipitation from NCAR-NCEP Reanalysis; the thick line represents the maximum variance in the 500-hPa height field, indicating the location of the storm track. Peak rainfall occurs along the southern margin of the storm track. Thus, the shift in the storm track presented by Yin [2005] naturally suggests a similar shift in the band of intense precipitation over the North Pacific. In the following, this intense precipitation and its behavior under climate change is examined.

The reanalysis will be used here as a reference for comparison of the various global climate models. While the NCAR-NCEP Reanalysis precipitation does not accurately depict local-scale precipitation features, it represents the

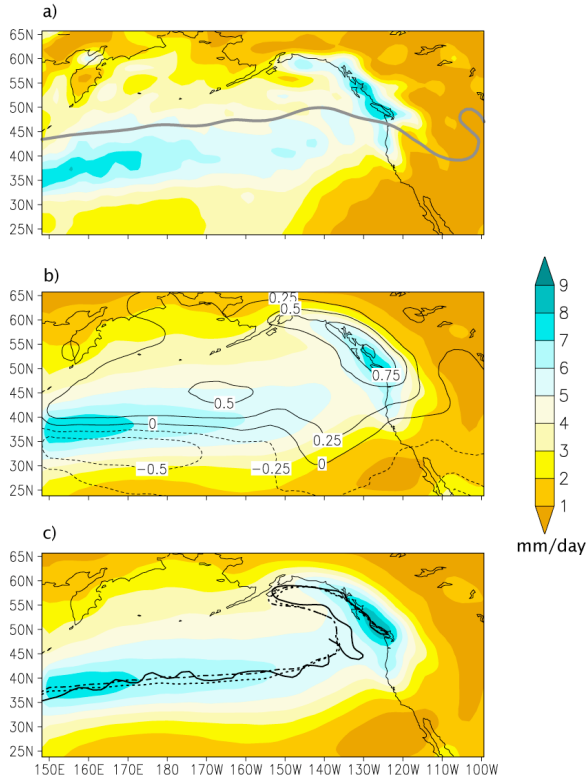


Figure 1. Precipitation tracks for a) the NCEP-NCAR reanalysis, b) model composite for 1950-2000, and c) model composite for 2050-2100. Thick line in a) indicates the storm track in 500-hPa heights. In b), contour lines indicate difference between 1950-2000 and 2050-2100 patterns. Lines in c) indicate the peaks of the NCEP-NCAR (solid), 1950-2000 (dash), and 2050-2100 (dash-dot) precipitation tracks.

precipitation pattern a climate model would produce if it accurately captured the planetary-scale weather patterns. The NCAR-NCEP Reanalysis shows a broad zonal band of precipitation extending between 35° and 45° N across the N. Pacific. This precipitation track curves northward as it reaches the N. American coast where it merges with a broad pattern of high precipitation extending from northern California to Alaska. The coastal precipitation pattern results from the interaction of the storm systems with the continental landmass, causing intense precipitation.

To combine the simulations from the 10 climate models described above, we form a composite of the individual models. Each climate model field is interpolated to the NCAR-NCEP Reanalysis grid and a weighted mean is formed. A model is weighted by the inverse mean squared difference between the 1950-2000 NDJ precipitation pattern for the model and the NCAR-NCEP Reanalysis. This approach assumes all models have useful information about the changes in the precipitation pattern, but that models that represent the present climate best should be given greater weight. Figure 1b shows the composite precipitation pattern from the 10 climate models for the period 1950-2000, which corresponds well to the NCAR-NCEP Reanalysis pattern.

| Model | Bias  | RMS  | Weight | North | Wet |
|-------|-------|------|--------|-------|-----|
| CCSM3 | 0.37  | 0.98 | 9.94   | N     | Y   |
| CGCM  | -0.06 | 0.82 | 14.13  | Y     | N   |
| CNRM  | 0.37  | 1.13 | 7.40   | Y     | Y   |
| CSIRO | 0.07  | 1.01 | 9.40   | N     | N   |
| ECHAM | 0.33  | 0.81 | 14.54  | Y     | Y   |
| GISS  | 0.17  | 1.24 | 6.23   | Y     | Y   |
| HADCM | 0.07  | 0.99 | 9.63   | Y     | Y   |
| IPSL  | 0.32  | 1.34 | 5.28   | Y     | N   |
| MIROC | 0.12  | 0.90 | 11.66  | Y     | Y   |
| PCM1  | 0.09  | 0.90 | 11.80  | N     | Y   |
| Comp  | 0.17  | 0.76 | --     | Y     | Y   |

Table 1 Summary statistics for precipitation composite computed by comparing the 1950-2000 simulation for each climate model with NCAR-NCEP reanalysis. Bias and RMS are in mm/day; the weight factor is expressed in percent. The final 2 columns indicate whether the precipitation track moves north and gets wetter under the A2 scenario.

The weights for the various models (Table 1) show that two models, CGCM and ECHAM5, are most heavily weighted. Furthermore, the RMS difference between the composite and NCAR-NCEP Reanalysis is smaller than for any individual model with a bias smaller than the mean of all models (0.19 mm/day), indicating that the model ensemble better represents the precipitation storm track than any individual model.

Using these weights, we then composite the precipitation simulated for the A2 climate scenario for 2050-2100 (Figure 1c; contour lines in Figure 1b show the difference between the 1950-2000 and 2050-2100 patterns). In the west, positive changes to the north and negative changes to the south indicate the track moves northward. At the eastern end, there are strong positive changes, showing intensification over western North America. The three thick lines in Figure 1c indicate the peak of the precipitation track for the reanalysis (solid), 1950-2000 (dashed) and 2050-2100 (dash-dot) composites. These tracks clearly show the northward shift at the western end of the track, which is consistent with the northward shift and intensification of the storm track under climate change [Yin, 2005]. The northward shift and intensification of precipitation in the composite is consistent across the 10 climate models. Seven models show a northward shift and seven show an intensification (Table 1). Only one model (CSIRO) shows neither change, with a decrease in precipitation. The agreement among models is not clearly related to performance in simulating the 20th Century precipitation pattern.

#### 4. Aleutian Low

The changes in the storm track over the North Pacific is also manifested in the position and intensity of the Aleutian Low (Figure 2a, 1950-2000 NCAR-NCEP reanalysis). This feature is the residual of the daily variability in sea level

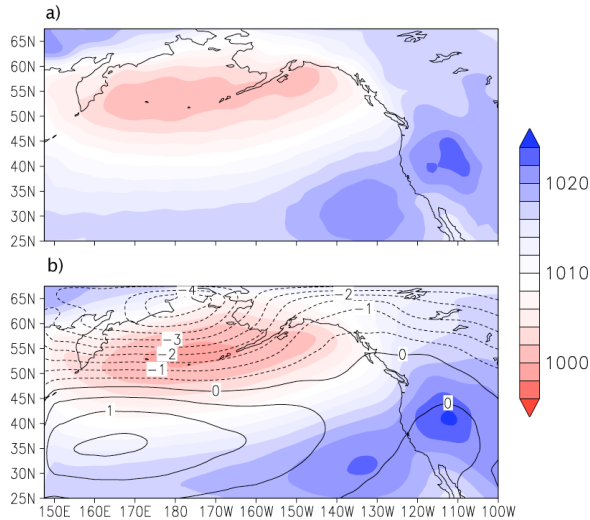


Figure 2. Aleutian Low for a) the NCEP-NCAR reanalysis, b) model composite for 1950-2000; contour lines indicate difference between 1950-2000 and 2050-2100 patterns.

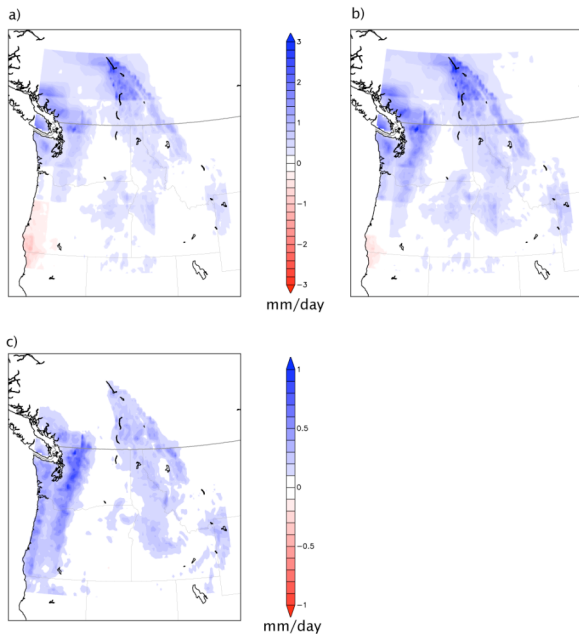


Figure 3. Difference in downscaled precipitation from 1950-2000 to 2050-2100 (a) precipitation only as predictor (b) precipitation and sea-level pressure as predictors. (c) Difference between (a) and (b); note different scale.

pressure produced by storm systems that propagate along the storm track during the cool season. Figure 2b shows a weighted composite of sea level pressure from the 20<sup>th</sup>-Century climate model simulations derived as for precipitation in Figure 1. Compared to reanalysis (Figure 2a), the composite sea level pressure produces a somewhat

deeper Aleutian Low, but the position and shape of the pattern are well represented. In particular, the direction of onshore flow to the Pacific Northwest and Alaska is captured quite well. Contour lines in Figure 2b indicate the difference between the 21<sup>st</sup> and 20<sup>th</sup> Century model composites. For the 21<sup>st</sup> Century A2 climate scenario, the models show a marked deepening of the Aleutian Low with increased gradients across the North Pacific. The dipole in the difference field indicates a shift in the position of the low to the north-northeast. These changes are consistent with the northward shift and intensification of the storm track indicated by the precipitation patterns discussed above.

Overland *et al.* [1999] discuss historic shifts in the Aleutian Low associated with decadal climate variability in the North Pacific. Natural variability is about double the magnitude of the pressure change from the late 20<sup>th</sup> Century to the late 21<sup>st</sup> Century (compare Figure 2c to Overland *et al.* [1999], Figure 4). Decadal variability is associated primarily with variability in the strength of the low, not its position. Thus, the changes in the Aleutian Low due to global climate change are not entirely analogous to the natural variability observed on decadal scales.

## 5. Regional Precipitation

The large-scale precipitation results above suggest that regional precipitation will increase over the Pacific Northwest for the 21<sup>st</sup> Century. The large-scale circulation patterns also change, which could modulate the precipitation response at regional scales. To illustrate these effects, we shall examine the regional precipitation downscaled from the ECHAM5 model using two downscaling methods. The ECHAM5 model is selected since it best represents the observed storm track and Aleutian Low and since a single model illustrates these interactions more clearly than a composite.

Widmann *et al.* [2003] and Salathé [2005] developed a method to downscale climate model simulations for Pacific Northwest precipitation that uses large-scale simulated precipitation as the primary predictor and large-scale sea-level pressure as a secondary predictor. In a simplified method, the effect of the pressure pattern is ignored and the downscaled precipitation is found by multiplying the simulated climate model precipitation by a scale factor defined on the regional-scale grid, 1/8-degree over the Pacific Northwest. The scale factor is computed for each calendar month as the ratio of the 1950-2000 mean simulated precipitation and the 1950-2000 observed precipitation on the 1/8-degree grid. For the full downscaling method, taking circulation into account, the scale factor is modified according to the leading modes of the sea-level pressure field to preserve the observed covariance between precipitation and circulation during the training period [Widmann *et al.*, 2003]. This covariance between sea-level pressure and precipitation is related to interactions between circulation and topography that affect the regional distribution of precipitation [Salathé, 2003].

Figure 3a shows the difference in downscaled precipitation from 1950-2000 to 2050-2100 using only precipitation as a predictor. Precipitation increases over most of the region except for the Oregon Coastal Range. The largest increases are seen over terrain, with a general trend for smaller increases in the southern part of the region. These changes are a direct consequence of the northward shift in the large-scale precipitation distribution with the storm track (Figure 1). Figure 3b is a similar difference map, but for the downscaling method that considers both precipitation and circulation as predictors. When circulation is taken into account, we find larger increases in precipitation for the 2050-2100 period. Figure 3c shows the difference between the two downscaling methods (circulation method minus precipitation-only method). In particular, relative to Figure 3a, we find greater precipitation over the North Cascades and extending southward along the Cascade Range. Increases in precipitation are also found over the Idaho Rockies, which was not indicated by the precipitation-only downscaling. This result suggests that the circulation changes produce more effective orographic enhancement of precipitation in the ECHAM5 climate change scenario than in the base climate. Transient wind patterns, not the mean pattern, are responsible for the change since the sea level pressure itself does not change over the region in the ECHAM5 simulation.

## 6. Conclusion

In accordance with Yin's [2005] result for the mid-latitude storm track, we find a northward shift and intensification of winter precipitation over the north Pacific in climate model simulations for the 21<sup>st</sup> Century. The Aleutian Low similarly shifts northward and intensifies. These changes have important implications for the precipitation climatology of the Western United States. Downscaling precipitation for the Pacific Northwest shows increases both due to large-scale effects captured in the global model and due to mesoscale orographic effects not represented in the global model. Changes in the transient circulation associated with the shifting storm track and Aleutian Low yield an increase in winter (NDJ) precipitation that is not captured by the global model.

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