A SIMPLE OROGRAPHIC PRECIPITATION MODEL FOR THE
PACIFIC NORTHWEST

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Abstract.—A two dimensional model of wind flow is used to compute vertical velocities using an accurate model of topography in the Pacific Northwest. A simple parameterization of precipitation is derived and used in conjunction with the model vertical velocities to produce estimated precipitation amounts. Two case studies are presented comparing the precipitation amounts estimated from the model with those actually observed.

INTRODUCTION

Accurate quantitative precipitation forecasts are important for professionals involved in winter recreation, avalanche control and highway maintenance. At present, forecasts of precipitation amounts for the Washington Cascades and Olympics are based on forecasters' experience in estimating the amount of precipitation that a synoptic event will produce. Computer generated quantitative precipitation forecasts are available twice daily for Seattle from the LFM (Limited Fine Mesh) and NGM (Nested Grid) models; however, these forecast amounts are not easily applied to mountain locations because mesoscale complex terrain, which the models can't resolve, results in widely varying precipitation amounts. Furthermore, even on a synoptic scale the model precipitation forecasts demonstrate only moderate skill.

This paper describes a simple orographic precipitation model for the Washington Cascades and Olympics. The precipitation model is based on the Mass and Dempsey (1985) windflow model.

LITERATURE REVIEW

To predict or diagnose mesoscale variations in precipitation, a detailed mesoscale windfield is necessary. Such a mesoscale windfield can greatly deviate from the synoptic scale flow. For example, the surface drag changes markedly as the air flows from the ocean on to land, with friction causing the air to decelerate and turn. Topographic features produce airflow deflection around obstacles, blocking by barriers, and channeling through gaps or valleys. Thermal effects further influence the mesoscale windfield. Differential heating and cooling produce land-sea breezes and slope winds, while heating or lifting of potentially unstable air at low levels creates convective activity. The interaction of the mesoscale windfield with topography determines a vertical velocity field, which in turn, is a factor in precipitation.

Several types of models have been developed to account for terrain effects. Three dimensional primitive equation models are currently too expensive to use on an operational basis; therefore, a two-dimensional model is used in this work.

Two-dimensional models are either x-z or x-y models. The x-z models consider flow over a barrier of infinite length with no variation along the y-axis, which runs parallel to the barrier. The x-y models, which allow the use of realistic terrain, assume a specified vertical variation of meteorological parameters.

Sarker (1967) and Elliott and Shaffer (1962) developed x-z models with parameterized precipitation, whereas Hobbs et al. (1973) included microphysical processes in their x-z model for the Washington Cascades. Rhea (1978) developed a steady-state multi-layer x-z model for Colorado which considers realistic topography, but does not allow any variation in the wind direction. The model uses the observed 700 mb level wind direction to pick one of 36 terrain maps that correspond to each 10 of azimuth. Precipitation resulting from forced
orographic lifting is calculated by following an airmass across the topography.

The accuracy of precipitation forecasts from x-z models is limited because it is unrealistic to assume that the wind direction does not vary through complex terrain. Therefore, x-y models, which use realistic terrain, provide the simplest method for forecasting mesoscale winds and precipitation.

Several x-y two-dimensional models have been developed (Lavoie (1974), Overland et al (1979), Danard (1977)). The Mass and Dempsey (1985) windflow model, which is a modified version of the Danard model, provides the wind field for the orographic precipitation model presented in this paper.

The Hass-Dempsey sigma coordinate model produces a slope parallel surface wind field. The vertical component of the wind vectors are calculated at each grid point in the domain using a method similar to Danard's (1976). $h_1$, $h_2$, $h_3$, and $h_4$ are the average heights of the terrain grid points surrounding the wind vector $(U)$ and $dx$ and $dy$ are the distances between adjacent grid points in the x and y direction, respectively (fig. 1). The slopes $dh/dx$ and $dh/dy$ are calculated such that:

\[ \begin{align*}
(1) \quad dh &= \frac{h_2 + h_4 - h_1 + h_3}{2} \\
(2) \quad dh &= \frac{h_1 + h_2 - h_3 + h_4}{2}
\end{align*} \]

Solving a right triangle and rearranging terms gives:

\[ \begin{align*}
(3) \quad w_{sx} &= u \cdot \frac{dh}{dx} \cdot \frac{\sqrt{\left(\frac{dh}{dx}\right)^2 + (dx)^2}}\\
(4) \quad w_{sy} &= v \cdot \frac{dh}{dy} \cdot \frac{\sqrt{\left(\frac{dh}{dy}\right)^2 + (dy)^2}}
\end{align*} \]

$w_s$, the slope induced surface wind vertical velocity, is the sum of the vertical components $w_{sx}$ and $w_{sy}$.

**MASS AND DEMPSEY WIND MODEL**

The Mass and Dempsey wind model calculates surface wind and temperature by integrating the horizontal momentum equation and surface temperature tendency equation in sigma coordinates. The model includes the effects of diurnal heating and cooling and friction. Model initialization requires the geopotential height and temperature at a reference level (usually 850 mb), taken from the National Meteorological Center (NMC) analysis for the model domain, and the free atmosphere lapse rate between 850 and 700 mb taken from a sounding near the inflow boundary. The model is run on a 75x74 point grid with a 7.5 km resolution.

**PRECIPITATION MODEL DESCRIPTION**

The orographic precipitation model addition to the Mass-Dempsey wind model assumes that precipitation is proportional to vertical velocity.

**Vertical Velocity Calculation**

The model vertical velocity can be decomposed into three individual vertical velocity components: the slope induced vertical velocity, which is the vertical component of the wind vectors from the Mass-Dempsey wind model; convergence vertical velocity, again from the wind model; and an imposed wind field vertical velocity, which is the vertical component of a separate geostrophic windfield imposed on the model terrain.
Expanding $\nabla \cdot U$ and assuming incompressibility gives

$$\frac{\partial w_c}{\partial z} = - \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)$$

where $\partial w_c/\partial z$ is the vertical velocity at the surface from convergence. $\partial u/\partial x + \partial v/\partial y$ are calculated from the $u$ and $v$ wind components generated by the Mass-Dempsey model. Surface wind convergence is assumed to decrease linearly with height ($H$), becoming zero when $H=2000m$. This figure was chosen because it is consistent with the 2000m topographic influence assumption in the Mass-Dempsey wind model. The component of the vertical velocity from convergence is found by integrating $\partial w_c/\partial z$ from the surface to 2000 m.

The vertical velocity components from the surface wind field ($w_s$ and $w_c$) are calculated using a 7.5 by 7.5 km terrain grid, whereas the large scale wind field vertical velocity is calculated with a 15 by 15 km terrain grid.

In a neutral or slightly stable atmosphere, a lifted air parcel will remain near the level it is lifted to with only slight downward motion on the lee side. Therefore, negative components of $w_s$, $w_{ls}$ and $w_c$ are divided by 2 before the total vertical velocity at each grid point is summed. This assumption is an attempt to compensate for the lack of three-dimensionality in the model. Although a rigorous investigation of this assumption might result in a more precise factor value, division by 2 markedly improves the model results.

**Precipitation Parameterization**

In the model, precipitation is assumed to be directly proportional to vertical velocity. A very simple precipitation parameterization scheme is employed.

Condensation is given by:

$$C = W_{total} \cdot \frac{dq_s}{dz} \cdot D \cdot t$$

where $D (1500m)$ is the depth of the lifted airmass and $t$ is the length of time that the airmass is lifted. $t$ varies from case to case depending on the duration of precipitation. $dq_s/dz$, the change in the saturated mixing ratio with height, can be taken directly from the pseudo-adiabatic chart or can be calculated using

$$\frac{dq_s}{dz} = (\frac{r_m + r_d}{L'}) \frac{c_p}{c_p}$$

where $c_p$ is the specific heat of dry air at constant pressure, $L'$ is the latent heat of vaporization, and $r_m$ and $r_d$ are the moist and dry lapse rates, respectively.

If all the precipitation that forms falls in the same grid where it is generated, precipitation ($P_T$) equals:

$$P_T = C \cdot E_1 + P_S$$

assuming a constant condensation to precipitation efficiency ($E_1$). $E_1$ equals .5 in the two cases presented in this paper. .5 was chosen as an average of the
mean condensation to precipitation efficiencies that Elliott and Shaffer (1962) calculated for the Santa Ynez (E=.35) and San Gabriel (E=.67) Mountains in California. P is the synoptic precipitation term, i.e., the amount of precipitation that falls over the ocean or flat terrain.

To account for particle fall trajectories and non-precipitating cloud droplets, a constant percentage of the condensation (R) in each grid is carried to the next grid downwind where it is combined with the condensation generated at that grid point. R is calculated as follows:

\[
E_2 = \frac{\text{constant percentage of remaining condensate carried by the wind to the next grid downwind}}{E_1}
\]

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\[
E_2 = \frac{\text{constant percentage of remaining condensate carried by the wind to the next grid downwind}}{E_1}
\]

\[
P_T = E_1 \cdot (C \cdot (F + R) + R) + P_S
\]

Thus far, the precipitation calculation assumes that the amount of moisture available for condensation is constant across the domain. For several predominant wind directions, i.e., SW to NW, the Cascades act as an efficient moisture barrier, with the saturated mixing ratio decreasing as an airmass moves eastward; therefore, F, a moisture depletion factor, is included in the precipitation calculation. For SW to NW wind directions, F is assigned such that condensation decreases by 30% from the Washington Coast to the eastern domain boundary.

\[
P_T = E_1 \cdot (C \cdot (F + R)) + P_S
\]

MODEL SIMULATIONS

The model was run for an area of the Pacific Northwest from 45 to 50 N latitude and from 119-126.4 W longitude. The domain, which encompasses the Olympic and Cascade Mountains, is ideal for testing an orographic precipitation model because of the large variations in precipitation. The smoothed terrain is shown in figure 2. The precipitation model results for two November 1984 cases are presented in this section. A moist southwesterly flow aloft characterizes the first case, while a more showery northwesterly flow aloft and well defined convergence zone in Puget Sound occurred in the second case.

Case 1: November 7, 1984 at 00 GMT
Southwesterly Large Scale Flow

A cold front crossed western Washington around 14 GMT on November 6th. Winds at Houlum on the Washington coast shifted from E to SW at frontal passage, and remained SW until 05 GMT on November 7th. At the 500 mb level, a trough of low pressure extended from the Gulf of Alaska southward off the west coast from November 5th through the 8th. The model run was for 00 GMT November 7th. The corresponding 850 mb analysis is presented in figure 3a. At 850 mb, a SW flow of 30-35 kts existed over the model domain with a trough of low pressure at 130°W longitude and a flat ridge of high pressure centered along 119°W longitude.

Figure 4a shows the observed surface winds. 10-25 kt winds prevailed along the coast and at Stampede Pass, while more southerly winds occurred in Puget Sound and east of the Cascades. The winds in the Strait of Georgia were southeasterly. The Hass-Dempsey wind model run (fig. 4b) duplicates the SW winds along the coast and the more southerly winds in Puget Sound and east of the Cascades; however, the model produces relatively strong SW winds down the leeward side of Vancouver Island and
The observed precipitation for a 24 hour period ending at 16 GMT November 7th is given in figure 5a. The heaviest precipitation occurred at Elwha Ranger Station on the north side of the Olympics and at Silverton in the north central Cascades. Relatively heavy precipitation areas covered the Olympic Mountains, the Cascades north-northeast from Mt. Rainier and the Mt. St. Helens area. Figure 5b shows the precipitation model run based on the equation 16 precipitation calculation. Many aspects of the model precipitation are qualitatively consistent with the observed precipitation. On the Olympic Peninsula the model realistically predicts relatively heavy precipitation on the SW side, with significantly less precipitation on the NE and E sides. The model did not produce the heavy precipitation measured at the Elwha Ranger Station. The model generally appears to duplicate the precipitation patterns over the Cascades. The Mt. Rainier area, Mt. St. Helens area, and the north central Cascades all experienced heavy precipitation, while several valley drainages received significantly less precipitation, most notably the Yakima and Wenatchee Rivers, and Lake Chelan east of the Cascade crest. Several of the precipitation gauge sites that recorded very light precipitation east of the mountains are in these drainages. The model predicts relatively heavy precipitation amounts over much of the higher terrain east of the Cascade crest. There are no precipitation gauge

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Figure 3. --NMC 850 mb height and temperature analysis for 00 GMT November 7, 1984. Height contours (solid lines) are in meters and temperature contours (heavy dashed lines) are in °C.

across the Strait of Georgia instead of reproducing the measured SE winds. Verification of the surface winds in the mountains is difficult because Stampede Pass is the only wind measurement available.

Figure 4. --a) Observed surface winds for 00 GMT November 7, 1984. On the wind flags, half barbs indicate 5 knots and full barbs equal 10 knots. b) Surface winds from Mass-Dempsey wind model run for 00 GMT November 7, 1984.
measurements to prove or disprove the predicted values; however, judging from mean annual rainfall maps and water resource predictions, the model is predicting too much precipitation for these areas. Table 1 gives observed and predicted precipitation for nine sites in Washington State. For six of the sites, the observed and predicted values are essentially the same. For Stevens Pass and Snoqualmie Falls the model precipitation is approximately 50-60% too high, while for Snoqualmie Pass it is 15% too low.

Case 2: November 14, 1984 at 00 GMT
Northwesterly Large Scale Flow, Puget Sound Convergence Zone

A cold front moved inland across the model domain on November 13th. Winds along the Washington coast shifted from E to WNW at 11 GMT November 13th, where they remained through 06 GMT the 14th. Southerly winds at 850 mb at 12 GMT November 13th were replaced by 20 kt NW winds by 00 GMT November 14th (fig. 6).

Figure 7a shows the observed surface winds for 00 GMT November 14th. 15-30 kt NW winds prevailed along the Washington Coast, western Vancouver Island and Georgia Strait with W winds to 35 kts through the Strait of Juan de Fuca. Winds flowing around the Olympic Peninsula met in Puget Sound, with the formation of a well developed convergence zone. The Mass-Dempsey wind model run (fig. 7b) duplicates the NW winds along the coast and down Georgia Strait as well as the W winds through the Strait of Juan de Fuca. The model produces strong convergence in Puget Sound; however, the position of the model's convergence is somewhat north of the observed convergence line, and the model does not duplicate any eastward component of the convergence surface winds. The model also produces a convergence zone in Georgia Strait. Although there are insufficient wind observations to verify the existence of this convergence zone, convergence zones in Georgia Strait have been observed (Mass, personal communication). Although the model reproduces the SW winds at Stampede Pass it is impossible to make any general conclusions about the accuracy of the model winds in the Cascades.

The observed precipitation for the 24 hour period ending at 1600 GMT November 14th is shown in figure 8a. Heavy convergence zone precipitation extends from Puget Sound to the Cascades. Additional areas of heavy precipitation occurred in the Mt. Rainier area and from Mt. St. Helens south to Mt. Hood. Other areas in Washington received relatively little precipitation. Figure 8b shows the
Table 1. --Observed and predicted precipitation for nine
stations in western Washington for the 24 hour period
ending at 1600 GMT November 7, 1984.

<table>
<thead>
<tr>
<th>STATION NAME</th>
<th>OBSERVED PRECIPITATION</th>
<th>PREDICTED PRECIPITATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seattle</td>
<td>.32</td>
<td>.35</td>
</tr>
<tr>
<td>Skykomish</td>
<td>.9</td>
<td>.85</td>
</tr>
<tr>
<td>Snoqualmie Pass</td>
<td>1.0</td>
<td>.79</td>
</tr>
<tr>
<td>Stampede Pass</td>
<td>.46</td>
<td>.48</td>
</tr>
<tr>
<td>Stevens Pass</td>
<td>.51</td>
<td>.76</td>
</tr>
<tr>
<td>Snoqualmie Falls</td>
<td>.4</td>
<td>.57</td>
</tr>
<tr>
<td>Paradise/Longmire</td>
<td>.69/.35</td>
<td>.52</td>
</tr>
<tr>
<td>Lake Wenatchee</td>
<td>.20</td>
<td>.21</td>
</tr>
<tr>
<td>Quillayute</td>
<td>.72</td>
<td>.67</td>
</tr>
</tbody>
</table>

The model run qualitatively reproduces the convergence precipitation in Puget Sound with the precipitation extension to the Cascades, as well as the areas near Mt. Rainier, Mt. St. Helens and Mt. Hood. The model produces many more areas with precipitation over the Cascades than are evident from the observations; however, the limited number of precipitation gauges in the mountains makes it impossible to test the accuracy of the model in these areas. The model produces relatively heavy precipitation along the west coast of Washington and Oregon as a result of frictional convergence as air flows from the ocean over land. The model also produces unobserved heavy precipitation on the east side of Vancouver Island, and along the northern Olympic Peninsula. Table 2 gives observed and model predicted precipitation for eight sites in Washington State. For four of the sites, the observed and predicted values are similar. For Skykomish and Stevens Pass, two sites that received heavy convergence precipitation, the model predicts significantly less precipitation than was observed. In contrast, the model overpredicts precipitation at Quillayute and Elwha Ranger Station.

DISCUSSION

The model duplicates the precipitation field for the November 7th southwesterly flow fairly well; however, the model underpredicts precipitation on the south and southeast slopes of the Olympic Mountains. The Mass-Dempsey model surface winds are deflected around the Olympics in response to adiabatic cooling and the associated pressure increase as the airflow initially moves upslope. As a result, there is very little slope induced vertical velocity contribution from the surface winds. Additionally, divergence of the surface winds on the windward slopes results in a negative vertical velocity component. Upslope winds can be increased on the south and southeast slopes of the Olympics by decreasing the stability of the lapse rate used to initialize the wind model; however, this solution also decreases channeling and blocking, which are positive features of the model. Elsewhere in Washington State, the model adequately duplicates the observed precipitation.

The model qualitatively reproduces the November 14th convergence precipitation that extended from Puget Sound to the
Figure 7. --a) Observed surface winds for 00 GMT November 14, 1984. On the wind flags, half barbs indicate 5 knots and full barbs equal 10 knots. b) Surface winds from Mass-Dempsey wind model run for 00 GMT November 14, 1984.

Figure 8. --a) Observed precipitation for 24 hour period ending at 1600 GMT November 14, 1984. Contour interval is .2 inches of water equivalent. b) Precipitation model run for 00 GMT November 14, 1984. Contour interval is .3 inches of water equivalent.
Table 2. --Observed and predicted precipitation for nine stations in western Washington for the 24 hour period ending at 1600 GMT November 14, 1984.

<table>
<thead>
<tr>
<th>STATION NAME</th>
<th>OBSERVED PRECIPITATION</th>
<th>PREDICTED PRECIPITATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quillayute</td>
<td>.01</td>
<td>.69</td>
</tr>
<tr>
<td>Elwha Ranger Station</td>
<td>.02</td>
<td>.50</td>
</tr>
<tr>
<td>Snoqualmie Pass</td>
<td>.4</td>
<td>.30</td>
</tr>
<tr>
<td>Stampede Pass</td>
<td>.44</td>
<td>.59</td>
</tr>
<tr>
<td>Paradise/Longmire</td>
<td>.84/.70</td>
<td>.73</td>
</tr>
<tr>
<td>Stevens Pass</td>
<td>.90</td>
<td>.23</td>
</tr>
<tr>
<td>Skykomish</td>
<td>1.4</td>
<td>0</td>
</tr>
<tr>
<td>Lake Wenatchee</td>
<td>.02</td>
<td></td>
</tr>
</tbody>
</table>

Cascades; however, the model's position of the convergence precipitation is north of the observed position. A more important problem with the Mass-Dempsey model surface wind field occurs to the northeast of the Olympic Mountains and Vancouver Island where the model produces very strong downslope winds that converge with winds channeled through the Strait of Juan de Fuca and through Georgia Strait. There is not an easy way to decrease the strong downslope winds in these areas while maintaining the lines of convergence across Puget Sound and southern Georgia Strait. The convergence in Puget Sound is influenced by a three-dimensional eddy in the lee of the Olympics that the wind model is unable to resolve.

In conclusion, the precipitation model does remarkably well given the simple precipitation parameterization that is used. Most of the significant deviations from observations can be attributed to errors with the wind model. The current version of the model may be a useful predictive tool for relatively two dimensional flow patterns; however, the model is not expected to do well in cases with significant three-dimensional structure because it cannot resolve three-dimensional variations of pressure and wind or moisture. The use of a three-dimensional wind model might significantly improve model results; however, three-dimensional wind models are currently too expensive to run on an operational basis. As computers become faster, it may become feasible to model precipitation in complex terrain by using a three-dimensional wind model and a relatively simple precipitation parameterization scheme.

LITERATURE CITED


