Prediction of Precipitation in Western Washington State

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16. ABSTRACT

This research adapted an orographic precipitation model developed during a previous WSDOT project (Report No. WA-RD-91.1) to run efficiently on an operational basis on a 386 personal computer, and made numerous model improvements. The precipitation model is being used operationally at the Northwest Avalanche Center in Seattle. Although the model is two-dimensional and employs simple precipitation parameterizations, it reproduced observed precipitation for two case studies remarkably well. The model should provide forecasters with useful guidance, especially during flow patterns that exhibit relatively two-dimensional characteristics.

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"Prediction of Precipitation in Western Washington State"

PREDICTION OF PRECIPITATION IN WESTERN WASHINGTON STATE

by

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Prepared for

Washington State Department of Tranportation

May 1991

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SUMMARY

The objective of the study was to adapt an orographic precipitation model developed during a previous WSDOT project (Report No. WA-RD-91.1) to run efficiently on an operational basis on a 386 personal computer, and to test further model improvements.

To achieve the research objectives, the following tasks were accomplished: 1) the model and terrain data files were transferred from a main frame to a 386 personal computer; 2) the wind and precipitation models were recompiled and debugged; 3) the model was run for numerous storms with model output statistically compared to observations; 4) a nested grid was set up for the Stevens and Snoqualmie Pass highway corridors; 5) interactive programs to run the model were written; 6) programs to automatically retrieve and interpret model input data were written; and 7) based on model runs during the 1989-90 and 90-91 winters, significant model improvements have been made.

The objectives of this research have been accomplished. The precipitation model is being used operationally at the Northwest Avalanche Center in Seattle. Although model output has been improved, there are two principle limitations to the accuracy of model forecast precipitation. The precipitation calculations are very dependent on terrain and on the surface wind. When it becomes available, the use

of more realistic terrain data may improve model output. Many of the precipitation model's deviations from observations can be attributed to the wind model. A two-dimensional model cannot resolve three-dimensional variations of pressure and wind or moisture. The use of a three-dimensional wind model, which may be feasible as computers become faster, might significantly improve model results.

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

The variation of precipitation in mountainous regions is important for highway maintainence and avalanche control. Site-specific quantitative precipitation forecasts are provided to Washington State Department of Transportation (WSDOT) personnel twice daily by the Northwest Avalanche Center (NWAC) for Mt. Baker, Stevens Pass, Snoqualmie Pass, White Pass and Crystal Mountain throughout the entire winter, with precipitation forecasts for Washington and Chinook Passes given during the fall and spring. Although the National Weather Service (NWS) forecast models do provide general precipitation information for Washington state, the precipitation quantities are calculated using highly smoothed topography and have little relevance for the mountains because they cannot resolve complex mesoscale terrain. To date, the quantitative precipitation forecasts issued by the Northwest Avalanche Center are based on the forecasters' experience in estimating how much precipitation a synoptic event will produce.

To provide forecasters' with an objective aid for precipitation forecasts, an orographic precipitation model for the Pacific Northwest was developed in 1986 with funding from the Washington State Department of Transportation in cooperation with the University of Washington Department of

Atmospheric Sciences. Model development and output from two case studies were presented in Technical Report WA-RD-91.1. The model, originally developed on a main frame computer and organized for research purposes, has been transferred to a personal computer and set up to run operationally at the Northwest Avalanche Center. As well, numerous improvements have been made to the model.

PROBLEM STATEMENT

The precipitation model is based on a two-dimensional wind model developed by Mass and Dempsey (1). A mesoscale windfield is necessary to calculate precipitation in complex terrain. Mesoscale winds interacting with topography result in vertical velocities which are a factor in precipitation. Windflow patterns in complex terrain are three-dimensional and very complicated. They result from the interaction of many forces, including but not restricted to the following: 1) changes in surface drag as air flows from the ocean on to land; 2) blocking by linear barriers; 3) channeling through gaps or valleys; 4) deflection around obstacles and; 5) differential heating or cooling. Although a three-dimensional windflow model should reproduce mesoscale winds more realistically than a two-dimensional windflow model, at present, it is too time consuming and expensive to run a three-dimensional mesoscale model on an operational basis. Therefore, a two-dimensional windflow model is used for this study. Numerous two-dimensional windflow models were discussed in report WA-RD-91.1. The reader should refer to that report for specific windflow model details. The Mass and Dempsey (1.) windflow model provides the surface windfield for the orographic precipitation model presented in this report. A vertical velocity field is calculated from the Mass and Dempsey windfield and a relatively simple precipitation parameterization is employed. During initial model development, the precipitation model was tested on two case studies. Although model generated precipitation quantities were reasonable for these two cases, for the model to be useful operationally, it was necessary to run the model for a wide range of synoptic weather conditions and to make changes indicated by the models' performance.

RESEARCH APPROACH

The objectives of this research were to adapt the previously developed orographic precipitation model to run efficiently on a high speed personal computer and to make model improvements based on its' performance. To accomplish these objectives, numerous tasks were identified. These tasks fall into six categories.

The wind and precipitation model files were transferred from a main frame to a personal computer, recompiled and debugged. The topography for model runs is based on terrain data from the National Center for Atmospheric Research. The original point data, recorded at 30 second intervals, was averaged to produce three independent topographic grids. A 7.5 km by 7.4 km grid and a 3.75 km by 3.7 km grid were produced that each extend from 45°-50° N latitude and 119-126.4° W longitude. A 1.9 km grid was produced from 47°-48° N latitude in order to calculate precipitation on a finer resolution along the Stevens and Snoqualmie Pass Highway corridors.

The model was run without making any changes for seven cases from the 1989-90 winter. A statistical verification program was written to compare model output with observed precipitation. Based on the models' performance, numerous improvements were tested. The model was transfered to the computer system at the Northwest Avalanche Center at the beginning of the 1990-91 forecast season and was run on a test basis throughout the winter. Significant additions and improvements were made to the model as a result of the models' performance. These improvements will be discussed in detail in the next section.

A nested grid was set up for precipitation calculations along the Stevens and Snoqualmie Pass highway corridors.

Convective parameterizations were researched and a simple scheme for convective precipitation was added.

Programs were written to automatically enter necessary model input data and to streamline the steps required by a forecaster to run the model. 850 mb and 700 mb level height and temperature gridded data from the National Weather Service Nested Grid Model (NGM) are automatically transferred twice daily from the University of Washington Department of Atmospheric Sciences. Mandatory level data from the 00 Z and 12 Z Quillayute, WA and Salem, OR soundings as well as forecast relative humidity data for Salem, OR, Seattle, WA and Vancouver, B.C. from the NGM model are transferred from the National Weather Service AFOS system. To run the precipitation model, a forecaster simply types one command and then answers a series of questions. This process takes about 1 minute to complete. The model requires approximately 20 minutes to run on a 386 computer equiped with a Weitek math coprocessor. Model results for 28 stations, including precipitation quantities and wind direction and speed, as well as detailed information for the Stevens and Snoqualmie Pass highway corridors and for 22 km by 22 km squares centered over Stevens and Snoqualmie Passes, are automatically printed out for each model run.

FINDINGS

The orographic precipitation model uses surface winds from the Mass-Dempsey wind model to calculate vertical velocities, which are proportional to precipitation. This chapter presents the Mass-Dempsey wind model, details the methods used to calculate vertical velocity, and discusses the precipitation parameterization. Where the current version of the model has not changed from the original, portions of the following model description are taken from Report WA-RD-91.1.

Mass and Dempsey (1) Wind Model

No physical changes were made to the Mass and Dempsey wind model during the current research; however, several changes were made to simplify entering input data and running the model. A description of the windflow model is followed by a discussion of the mechanical changes made for running the 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 using a second-order Adam's Bashforth scheme. The horizontal momentum equation includes terms for advection, Coriolis acceleration, the pressure gradient force, frictional drag and horizontal diffusion. Changes in surface temperature occur by temperature advection, adiabatic heating and cooling in response to changes in surface pressure, diabatic heating and cooling, and horizontal diffusion. Surface pressure, an unknown in both equations, is calculated by integrating the hydrostatic equation between the surface and reference pressure level (850 mb).

Model initialization requires the geopotential height and temperature taken from a reference level (850 mb), and the free atmosphere lapse rate between 850 and 700 mb taken from a sounding near the inflow boundary. Gridded data from the National Meteorological Center Nested Grid Model (NGM) provides geopotential height and temperature input data. The model currently runs on analysis data or on the 6, 12, 18, or 24 hour prognoses. For analysis runs, the free atmosphere lapse rate is taken from the Quillayute, WA sounding. For prognosis runs, the free atmosphere lapse rate is calculated from gridded data at 47.5°N latitude and 125°W longitude.

The model equations are integrated to steady state using a time step of 180 seconds, requiring approximately 240 time steps. The model is run on a 75 by 74 point grid with a 7.5 km resolution. Although a higher resolution would be preferable for the precipitation model, the hydrostatic balance assumed for the wind model by Mass and

Dempsey limits the possible grid length reduction. Model initialization and integration requires approximately 20 minutes on a 25 or 33 mHz 386 personal computer equiped with a Weitek math coprocessor if the average tendencies of the wind components are required to fall below .00003 m/s.

Several mechanical changes were made to automate running the wind model. As a result, many parameters are assigned values, which allows less case specific input. Model output is not significantly affected because the parameters are given realistic values that change with season or the time of day of the model run. For example, the length of day and night are assigned values by month.

The wind model is initially run with 25 geopotential heights and temperatures as input. If the average tendencies of the wind components do not converge, the wind model is rerun with the average geopotential height and temperature gradient along a north-south line at 125° W longitude from 45°-50° N latitude. If a front exists diagonally across this line, the average tendencies of the wind components will again not converge, and the model run is aborted.

Precipitation Model Description

The orographic precipitation model addition to the Mass-Dempsey wind model assumes that precipitation is proportional to vertical velocity. In this section, details of the vertical velocity calculation are described, followed by a discussion of the precipitation parameterization used as well as the changes that have been made to the model.

Vertical Velocity Calculation

The model vertical velocity can be decomposed into three individual vertical velocity components; 1) the slope induced vertical velocity, which is the vertical component of the wind vectors from the Mass-Dempsey wind model, 2) convergence vertical velocity, again from the wind model, and 3) an imposed wind field vertical velocity, which is the vertical component of a separate geostrophic windfield imposed on the model terrain.

There have been no changes made to the methods for calculating the two vertical velocities from the Mass-Dempsey wind field. The following discussion of these methods is taken from Report WA-RD-91.1.

1) The Mass-Dempsey sigma coordinate model produces a slope parallel surface wind field. The vertical components of the wind vectors are calculated at each grid point in the domain using a method similar to Danard's (2). 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 symbols used in the

following equations are summarized in Appendix A. The slopes dh/dx and dh/dy are calculated such that:

$$\frac{dh}{dx} = \frac{h_2 + h_4}{2} - \frac{h_1 + h_3}{2} \qquad (1)$$

$$\frac{dh}{dy} = \frac{h_1 + h_2}{2} - \frac{h_3 + h_4}{2} \qquad (2)$$

From dh/dx and dx, the hypotenuse of the right triangle shown in Figure 2 is calculated:

$$hypx = \sqrt{\left(\frac{dh}{dx}\right)^2 + (dx)^2} \qquad (3)$$

It follows that:

$$\frac{u}{hypx} = \frac{wsx}{\frac{dh}{dx}} \qquad (4)$$

Rearranging terms gives:

$$wsx = u \frac{dh}{dx} / hypx \qquad (5)$$

wsy is calculated using a similar logic:

$$wsy = v \frac{dh}{dy} \Bigg/ \sqrt{\left(\frac{dh}{dy}\right)^2 + (dy)^2} \qquad (6)$$

ws, the slope induced surface wind vertical velocity, is the sum of the vertical components wsx and wsy.

$$ws = wsx + wsy \qquad (7)$$

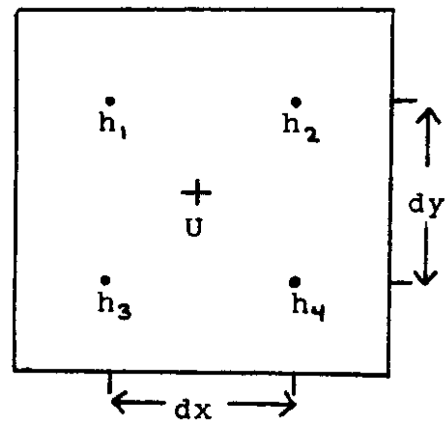

Figure 1. Grid height configuration for vertical velocity calculation

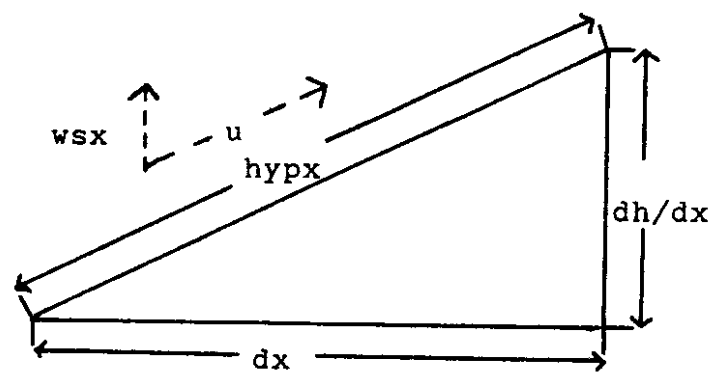

Figure 2. Wind vector (u) and vertical velocity (wsx) relation to terrain paramters dx and dh/dx

2) The vertical velocity from convergence is calculated using the velocity divergence form of the continuity equation.

$$\frac{1}{\rho}\frac{d\rho}{dt} + \nabla \cdot U = 0 \tag{8}$$

Expanding $\nabla \cdot U$ and assuming incompressibility gives

$$\frac{\partial w}{\partial z} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{9}$$

where $\partial w/\partial z$ 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 is 2000 meters above the topography. This figure was chosen because it is consistent with the 2000 meter topographic influence assumption in the Mass-Dempsey wind model. The component of the vertical velocity from convergence is found by integrating $\partial w/\partial z$ from the surface upward 2000 meters.

3) The winds produced by the Mass-Dempsey model result from the interaction of the surface flow with complex terrain. In high elevation terrain, momentum from higher levels in the atmosphere is also felt; therefore, a separate

wind field representing the large scale flow is imposed on the model terrain.

The large scale wind field has a constant wind direction with height. For model runs using the NGM analysis for input data, the wind direction of the large scale wind field is the average direction of the 850 and 700 mb level winds from the Quillayute sounding. If an NGM prognosis is used for model input, the large scale wind direction is calculated from the 850 and 700 mb level gridded data for that model run centered at 47.5°N latitude and 125°W longitude.

The variation of wind speed with height, which is case dependent, fits the vertical wind profile measured by the radiosonde ascent for analysis runs and calculated from the gridded data for prognosis runs. In order to eliminate the effect of the surface flow from the large scale windfield, the surface wind speed is subtracted at all levels from the vertical wind speed profile. The surface wind speed is taken from the Quillayute sounding for analysis runs and is taken for Quillayute's location from the Mass-Dempsey wind model windfield for prognosis runs. At each grid point, a wind speed that depends on grid point elevation is assigned. The vertical components of the wind vector (w_{Lsx} and w_{Lsy}) are then calculated.

$$w_{LSx} = u_{LS} \frac{dh}{dx} \tag{10}$$

$$w_{LSy} = v_{LS} \frac{dh}{dy} \tag{11}$$

u_{LS} and v_{LS} are the u and v components of the large scale wind field. w_{LS}, the vertical velocity resulting from the large scale wind field, is the sum of the vertical components w_{LSx} and w_{LSy}:

$$w_{LS} = w_{LSx} + w_{LSy} \tag{12}$$

The w_{LS} calculation was performed on a 15 x 15 km terrain grid with the wind vector normally 3.75 km inside the upwind terrain boundary. It was determined during initial model development that this method produced the best results. This finding was confirmed during recent model runs when the primary mechanism for precipitation was orographic lifting and the flow pattern was relatively two-dimensional. When significant convection occured, better results were produced with the wind vector centered in the 15 x 15 km terrain grid. Depending on the degree of orographic versus convective lifting expected by a forecaster, the model is run either with the wind vector 3.75 km inside the upwind terrain boundary or centered in the terrain grid.

Downward motion on the lee side of a barrier is typically less than the vertical velocities on the windward side, especially when the airmass involved is neutral or slightly stable. A strong inversion typically exists east of the Washington Cascades during the winter. The associated very stable cold air inhibits downward motion. To account for these factors and to compensate for the lack of three-dimensionality in the model, negative components of ws, wls and wc are divided by 4 before the total vertical velocity in each grid point is summed. This factor has been increased from 2 since initial model development. The value 4 was selected based on model verification. This factor would be expected to produce the best results during relatively two-dimensional flow patterns involving slightly stable airmasses. It does less well when; 1) a deep layer of cold air exists east of the Cascades, in which case air moving eastward across the Cascades experiences little or no downward motion, or 2) the airmass is unstable.

Precipitation Parameterization

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

Condensation, ie, the amount of water (in meters) condensed out in lifting an air parcel from the surface upward 1500 m, is given by:

$$c = w_{total} \cdot \frac{dq_s}{dz} \cdot D \cdot t \qquad (13)$$

where w_{total} is the total vertical velocity, dq_s/dz is the change in saturated mixing ratio with height, D (1500 m) is the depth of the lifted airmass and t is the length of time that the airmass is lifted. Hill et al (3) concluded that 80% of the orographic enhancement of precipitation occurs within 1500 meters above the terrain. Although D equals 1500 meters in the model, the actual value of D is not critical because it is a constant. t varies from case to case depending on the expected duration of precipitation. dq_s/dz is calculated using:

$$\frac{dq_s}{dz} = \left(\Gamma_m - \Gamma_d\right) \frac{c_p}{L} \qquad (14)$$

where c_p is the specific heat of dry air at constant pressure, L is the latent heat of vaporization, and Γ_m and Γ_d are the moist and dry lapse rates, respectively.

The saturated mixing ratio often varies significantly from north to south depending on many factors, including the trajectory of weather systems. If a weather system moves inland primarily through British Columbia, it is likely that the northern Washington Cascades will receive substantially more precipitation than will the Mt. Hood area because most of the weather system's associated moisture is to the north of the region. To allow for north-south moisture differences, dq_s/dz is calculated from the Quillayute and Salem soundings for analysis runs. The Port Hardy sounding, north of the model's domain, is not currently used for this calculation; however, its' inclusion would give further detail to the moisture field. For prognosis runs, dq_s/dz is calculated from gridded data at 45° N, 47.5° N and 50° N latitude. Based on the values at these points, dq_s/dz is varied linearly north-south across the model's domain.

The airmass is lifted dry adiabatically until saturation is reached. For analysis runs, the 850 mb temperatures and dew point depressions for Salem and Quillayute are used to calculate the amount of lifting necessary to reach saturation. Based on the values for these two stations, the amount of lifting required to reach saturation is altered north-south through the model's domain. A similar approach is used for the prognosis runs; however, since specific dew point depression data is not available, NGM generated relative humidity forecasts corresponding to the time of the model run provide equivalent information.

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

$$P_T = C \times E_1 + P_s \qquad (15)$$

assuming a constant condensation to precipitation efficiency (E_1). E_1 equals .5. No change has been made to E_1 since initial model development. P_s is the synoptic precipitation term, ie, the amount of precipitation that would be expected if the terrain were flat or if precipitation were measured over the ocean.

Under strong wind conditions, or in winter when precipitation may fall as snow, it is unrealistic to assume that all precipitation falls vertically to the ground. In addition, small ice crystals or water droplets may be carried considerable distances downwind before they precipitate or evaporate. 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:

$$R = (C - C \times E_1) \times E_2 \qquad (16)$$

E_2 is the condensation carrying efficiency, defined as the percentage of remaining condensate that is carried by the wind to the next grid downwind. E_2 is given a value of .75. Although the actual downwind transport of condensation is dependent on the wind speed and temperature, suggesting that E_2 should be varied from case to case, the total precipitation calculation is not very sensitive to the value of E_2. Taking account of R, precipitation equals:

$$P_T = E_1(C + R) + P_S \qquad (17)$$

The precipitation calculation starts at the upwind border of the domain and progresses in the direction of the large scale flow.

Thus far, the precipitation calculation assumes that the amount of moisture available for precipitation is constant west to east across the domain. For SSW to NNW wind directions, the Cascades act as an efficient moisture barrier, with the saturated mixing ratio decreasing as an airmass moves eastward. To compensate for decreasing moisture availablity, F, a moisture depletion factor, is included in the precipitation calculation.

In the original version of the model, F was assigned such that condensation decreased linearly by 30% from the Washington Coast to the eastern domain boundary during SW through NW wind directions. Based on model verification by geographic region and climatological annual precipitation maps, a more specific moisture depletion function is now used. Figure 3 gives graphic details of this function. At all latitudes, 100% of generated condensation is included in the precipitation calculation from the model's western domain boundary to the foothills of the Cascades. This line is drawn approximately through Skykomish (longitude 121° 20' W) in the north and Mt Hood (longitude 121° 40' W) in the south. Because the Northern Washington Cascades are substantially wider than the Southern Washington and Oregon Cascades, these two regions are dealt with differently. From Stevens Pass north, condensation is decreased linearly by 15% between longitude 121° 20' W and the Cascade crest. Condensation is decreased by an additional 52% from the Cascade crest to longitude 120° 33' W (approximately through Winthrop and Chelan). From Snoqualmie Pass south, condensation decreases by 67% between the Cascade foothills at longitude 121° 40' W and a north-south line through Cle Elum at longitude 120° 50' W.

The model was tested with F decreasing linearly and exponentially from the Cascade crest eastward. The linear decrease produced the best results.

Although the rain shadow in the lee of the Olympic Mountains shifts with wind direction, the Olympics were not included in the moisture depletion factor for two reasons. 1) There are relatively few stations recording precipitation around the Olympic Mountains, making it difficult to

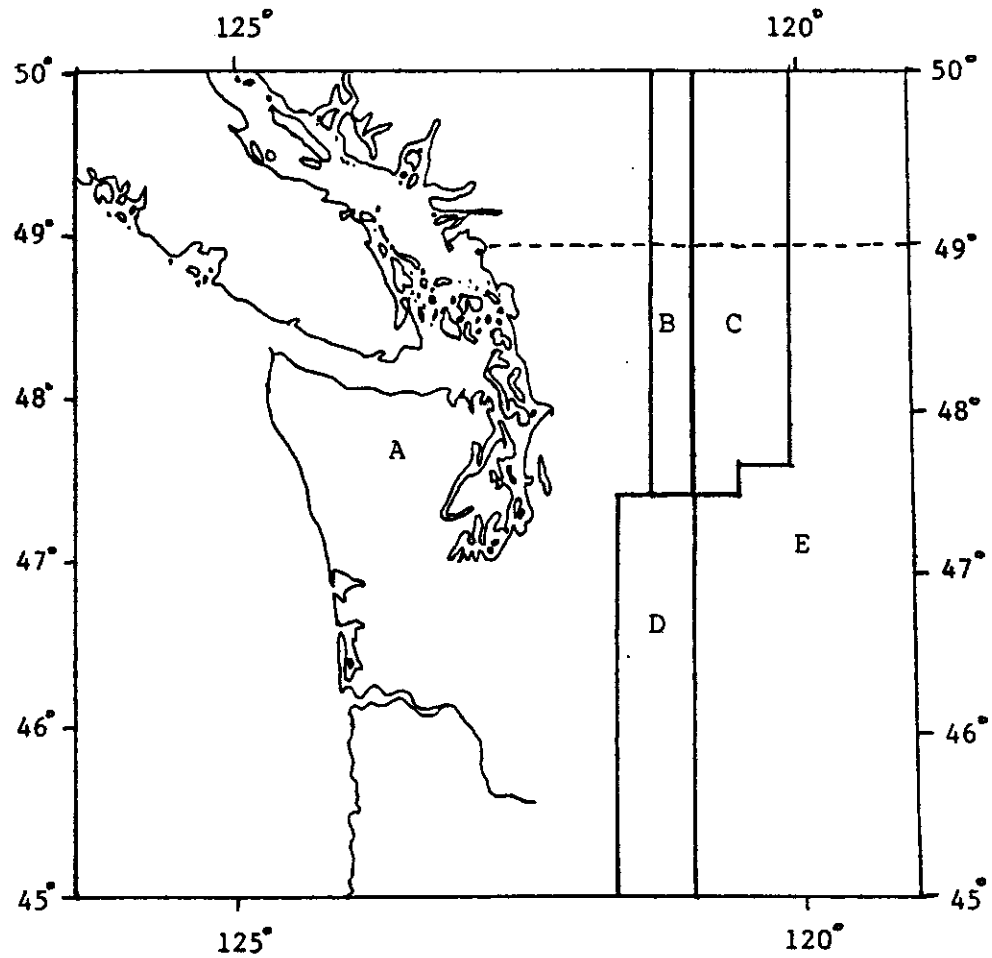

Figure 3. Moisture depletion function. The following moisture depletion factors (F) are used in the geographic regions A-E.

A) F=0 (100% moisture available for condensation)
B) F=-.15 (moisture decreases linearly by 15% between western and eastern boundary)
C) F=-.52 (moisture decreases linearly by 52% between western and eastern boundary)
D) F=-.67 (moisture decreases linearly by 67% between western and eastern boundary)
E) F=0 (33% of moisture that was available for condensation in region A is available in region E)

determine an empirical factor. 2) Negative vertical velocities from the imposed large scale wind field effectively account for the rain shadow (Report WA-RD-91.1).

INTERPRETATION, APPRAISAL AND APPLICATION

The model was run for an area of the Pacific Northwest from 45°-50° N latitude and from 119°-126.4° W longitude. The domain, which encompasses the Olympic and Cascade Mountains, as well as the dry region east of the Cascades, is ideal for testing an orographic precipitation model because it experiences large variations in precipitation. Mean annual precipitation changes from over 200 inches in the Olympics to 10 inches east of the Cascades. Relative precipitation differs from storm to storm as well, with Crystal Mountain, for example, often receiving significantly less precipitation than Stevens or Snoqualmie Passes; however, this relationship can be reversed.

The model domain is divided into 75 by 74 grid points, with each grid square measuring approximately 7.5 km on a side. The model terrain contains average height data for each grid square calculated from 30 second point data available through the National Center for Atmospheric Research (NCAR). The smoothed terrain data is shown in Figure 4.

Several significant features stand out in the averaged terrain. The Olympic Mountains, which are the northern extention of the coast range, extend above 1500 m with the Strait of Juan de Fuca to their north and the low elevation Chehalis gap to the south. Puget Sound separates the

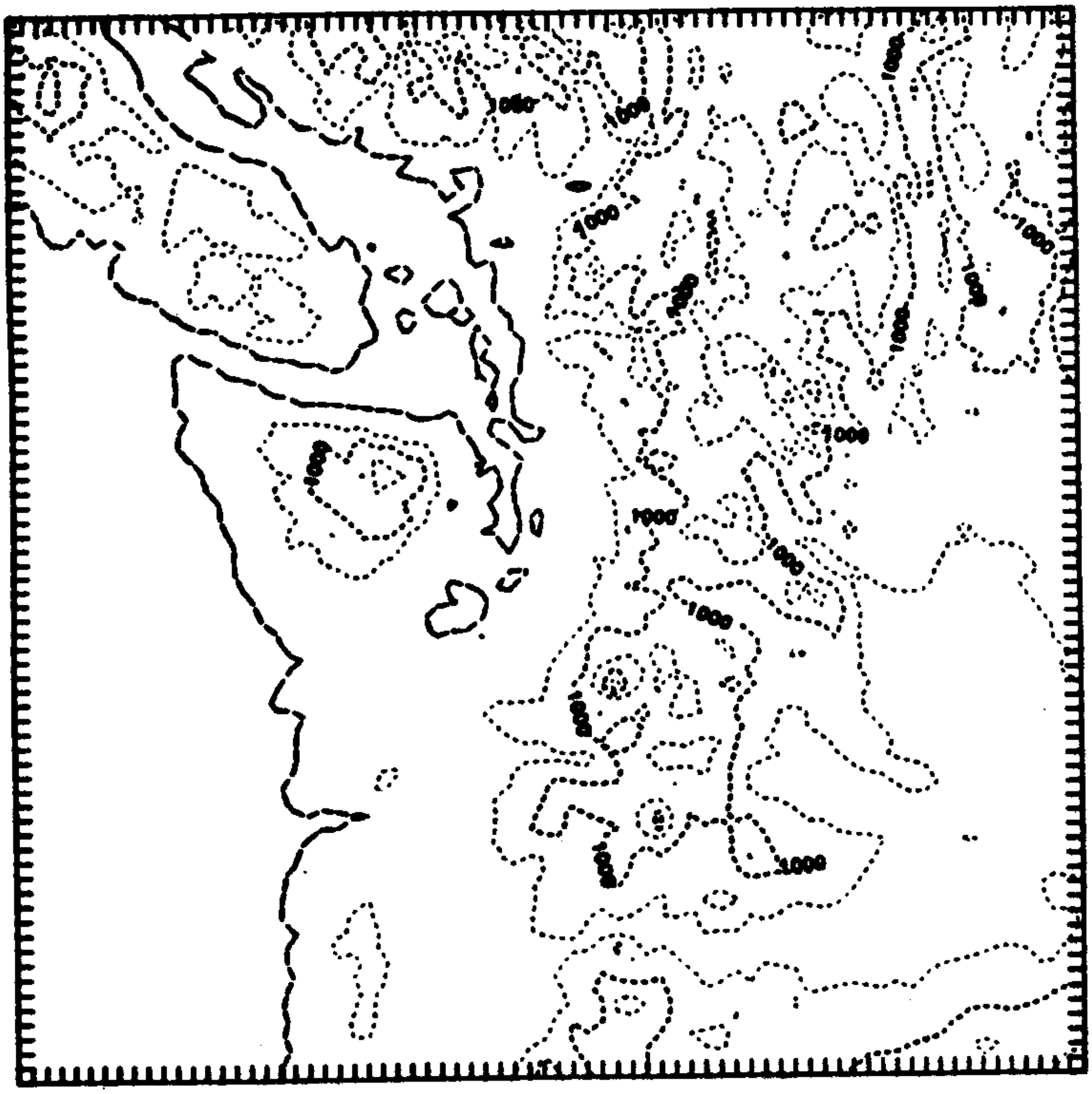

Figure 4. Smoothed topography derived from 7.5 km terrain data used for wind and precipitation model runs. Contour interval is 500 m.

Olympics from the Cascade range, which extends from the Canadian border south into Oregon. A line of volcanoes runs north-south along the western side of the Cascades with Mt Baker, Mt Rainier and Mt Adams clearly distinguishable on the smoothed model terrain. The north Cascades, with a large area above 1500 m, are significantly wider and generally higher than the southern Washington and Oregon Cascades. There are several passes or cuts through the Cascades, with the Columbia River providing the deepest channel; however, Snoqualmie and Stevens Pass, as well as others, form gaps in the range. East of the Cascades lies a plateau that is approximately 1000 meters high.

In order to produce more detailed precipitation output for Stevens and Snoqualmie Passes, the precipitation model is also run on a smaller scale terrain grid measuring 1.9 km on a side. Vertical velocities are calculated by superimposing the small scale terrain on the 7.5 km surface wind field. Otherwise, the precipitation calculation is similar to that for the 7.5 km grid.

The period from March 7th through March 24th 1991 produced a wide variation in synoptic weather, with the upper level flow ranging from northerly counterclockwise through southeasterly. The main storm track, which initially moved through British Columbia, shifted south over the Pacific Northwest and then further south into

California. A significant split developed in the upper level flow in the middle of the period and continued through the 24th. Precipitation occured during three multi-day periods which were separated by 1 to 3 dry days. The precipitation model results for two March 1991 cases are presented in the following section. A moderate north-northwesterly flow aloft and showery conditions characterized the first case, while a moist west-southwesterly large-scale flow occured during the second case. These two cases were chosen because most of the precipitation that occured during the station observation periods could be attributed to a single model run. The precipitation model was additionally run at 12 hour intervals for the period from March 7th through March 24th. Total observed precipitation for the period is compared to model precipitation for 19 stations.

MODEL SIMULATIONS: 2 CASE STUDIES

CASE 1: 00 GMT MARCH 7, 1991, NORTH-NORTHWESTERLY LARGE-SCALE FLOW

At 00 GMT on March 7th, an upper-level ridge of high pressure existed over southeast Alaska and northern British Columbia with a north-northwesterly flow aloft over Washington and Oregon. The corresponding 850 mb level analysis is presented in Figure 5. 15 kt nortwesterly winds were recorded by the soundings at Salem, Quillayute and Port

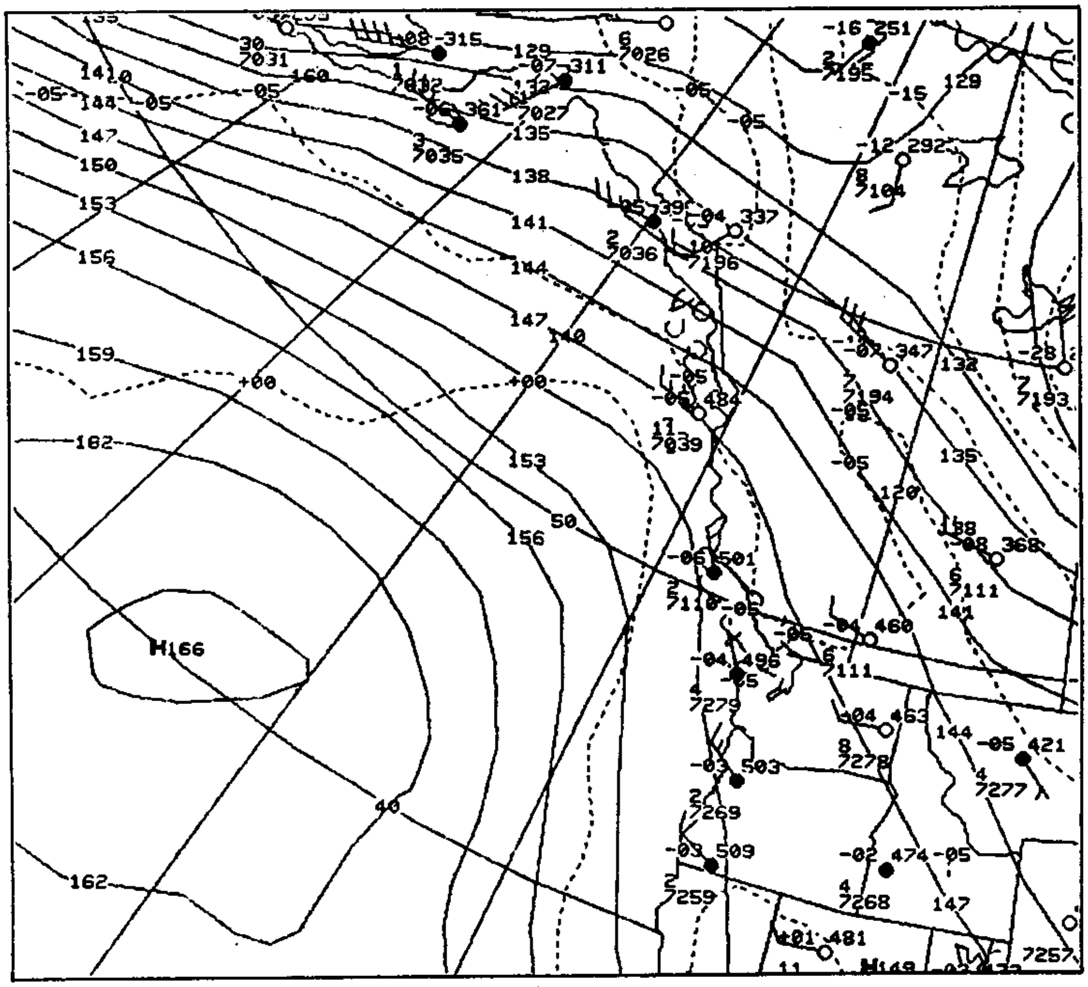

Figure 5. NMC 850 mb height and temperature analysis for 00 GMT March 7, 1991. Height contours (solid lines) are drawn at 30 m intervals and are labeled in tens of meters: temperature contours (dashed lines) are labeled in degrees Celsius.

Hardy. The relatively flat ridge of high pressure that dominates the analysis is centered along 130°-135° W longitude.

The sounding for 00 GMT March 7th at Quillayute is shown in Figure 6. The sounding is nearly saturated at 900 mb, but is relatively dry above that. Additionally, the air is weakly unstable from the surface to 950 mb. Above 950 mb, the air becomes increasingly stable.

Surface winds from the Mass-Dempsey wind model are compared to observed surface winds at 00 GMT March 7th for 19 National Weather Service (NWS) and Northwest Avalanche Center (NWAC) sites in Table 1. The locations of the model verification stations are shown in Figure 7 and detailed in Table 2. Although model winds compare favorably with observed winds for stations ranging from Quillayute and Astoria near the Pacific coast to Bellingham in Puget Sound and Stevens Pass in the Washington Cascades, for several stations the model winds do not reproduce the observed winds.

The weather on March 7th was showery. The imposed large scale wind field winds, taken from the Quillayute sounding (Fig. 8), were relatively weak below about 6000 feet and from 6000-9000 feet measured 15 kts. Observed surface wind directions were not constant at many stations. The wind direction at Mt Hood Meadows shifted from 219° to

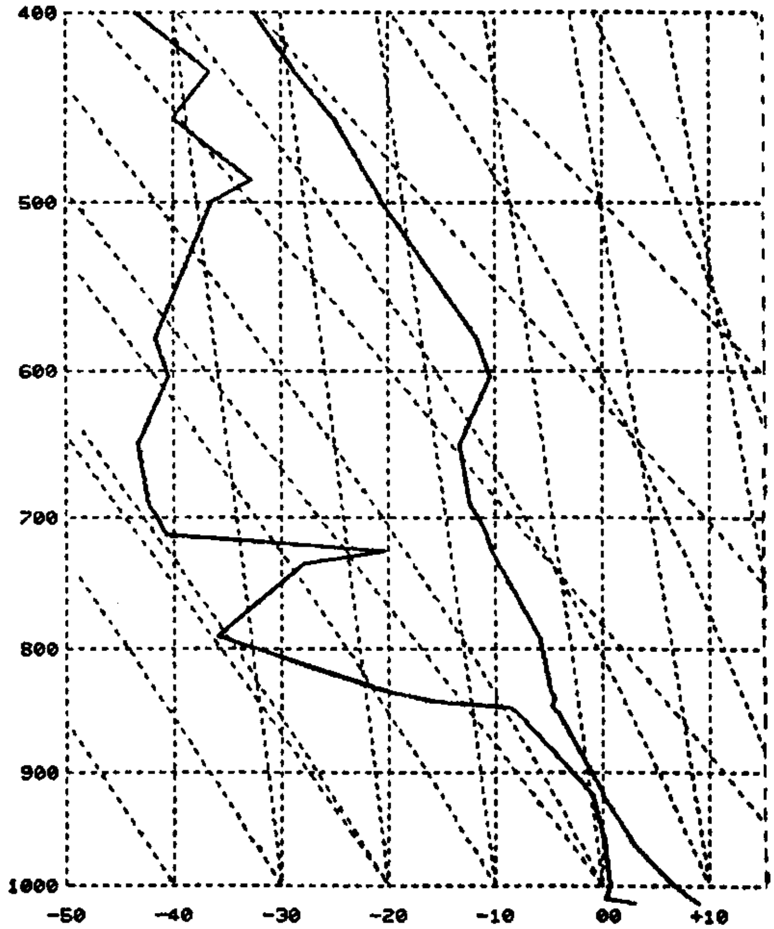

Figure 6. Quillayute, Washington radiosonde sounding for 00 GMT March 7, 1991.

TABLE 1 Observed and model predicted surface winds for 14 sites in western Washington and Oregon for 00 GMT March 7, 1991

STATION NAME	OBSERVED WINDS	PREDICTED WINDS
Stevens Pass	223° 3 kts	220° 3 kts
Mission Ridge	261° 3 kts	226° 11 kts
Snoqualmie Pass	270° 6 kts	197° 4 kts
Stampede Pass	300° 6 kts	256° 6 kts
Crystal Mountain	296° 10 kts	224° 1 kt
Paradise/Mt. Rainier	220° 4 kts	275° 6 kts
Mt. Hood Meadows	219° 3 kts	164° 9 kts
Government Camp	313° 9 kts	188° 5 kts
Quillayute	330° 6 kts	350° 9 kts
Astoria	310° 12 kts	229° 4 kts
Bellingham	280° 4 kts	289° 3 kts
Seattle	150° 4 kts	211° 7 kts
Olympia	020° 5 kts	260° 8 kts
Yakima	230° 5 kts	343° 2 kts

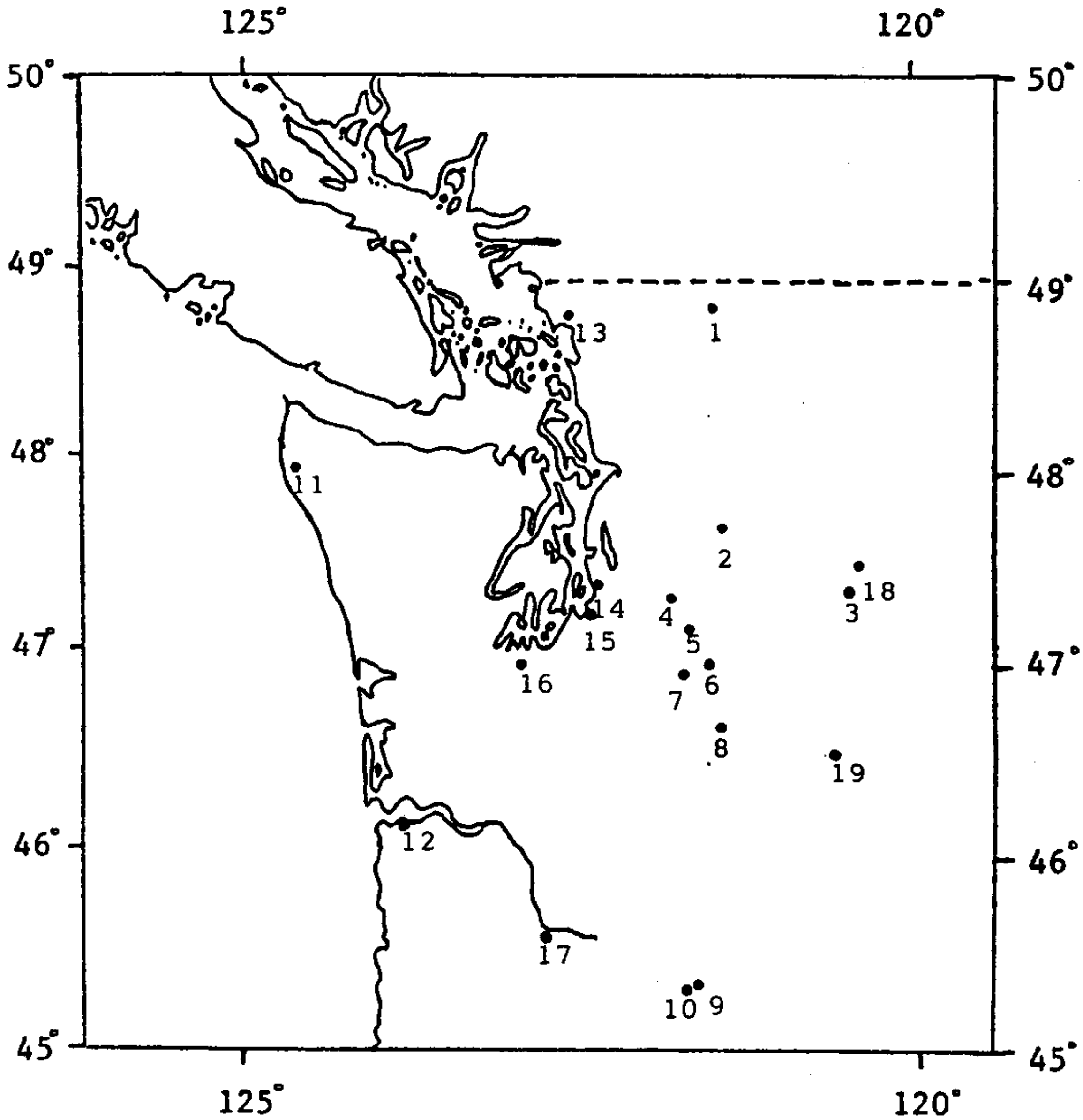

Figure 7. Locations of the stations used for model verification. Numbers refer to the station ID's given in Table 2.

TABLE 2. Precipitation gauge sites used for model verification. Latitude (LAT), longitude (LONG), actual terrain elevation (TER ELEV) and smoothed model topography elevation (MOD ELEV) are listed for each station.

ID	STATION NAME	LAT	LONG	TER ELEV (FT)	MOD ELEV (FT)
1	MT BAKER SKI AREA	$48^\circ 52'$	$121^\circ 41'$	4500	4766
2	STEVENS PASS	$47^\circ 44'$	$121^\circ 05'$	4070	3634
3	MISSION RIDGE	$47^\circ 18'$	$120^\circ 24'$	5300	5924
4	SNOQUALMIE PASS	$47^\circ 25'$	$121^\circ 25'$	3020	3224
5	STAMPEDE PASS	$47^\circ 17'$	$121^\circ 20'$	3958	3047
6	CRYSTAL MOUNTAIN	$46^\circ 56'$	$121^\circ 29'$	4400	4838
7	PARADISE/MT RAINIER	$46^\circ 47'$	$121^\circ 44'$	5427	4648
8	WHITE PASS	$46^\circ 38'$	$121^\circ 23'$	4500	4759
9	MT HOOD MEADOWS	$45^\circ 19'$	$121^\circ 40'$	5350	5061
10	GOVERNMENT CAMP	$45^\circ 18'$	$121^\circ 44'$	3600	3992
11	QUILLAYUTE	$47^\circ 57'$	$124^\circ 33'$	179	98
12	ASTORIA	$46^\circ 09'$	$123^\circ 43'$	30	184
13	BELLINGHAM	$48^\circ 48'$	$122^\circ 32'$	149	69
14	SEATAC AIRPORT	$47^\circ 27'$	$122^\circ 18'$	450	282
15	TACOMA	$47^\circ 15'$	$122^\circ 25'$	25	182
16	OLYMPIA	$46^\circ 58'$	$122^\circ 54'$	192	197
17	PORTLAND	$45^\circ 38'$	$122^\circ 35'$	26	180
18	WENATCHEE	$47^\circ 24'$	$120^\circ 12'$	1229	889
19	YAKIMA	$46^\circ 34'$	$120^\circ 32'$	1064	1200

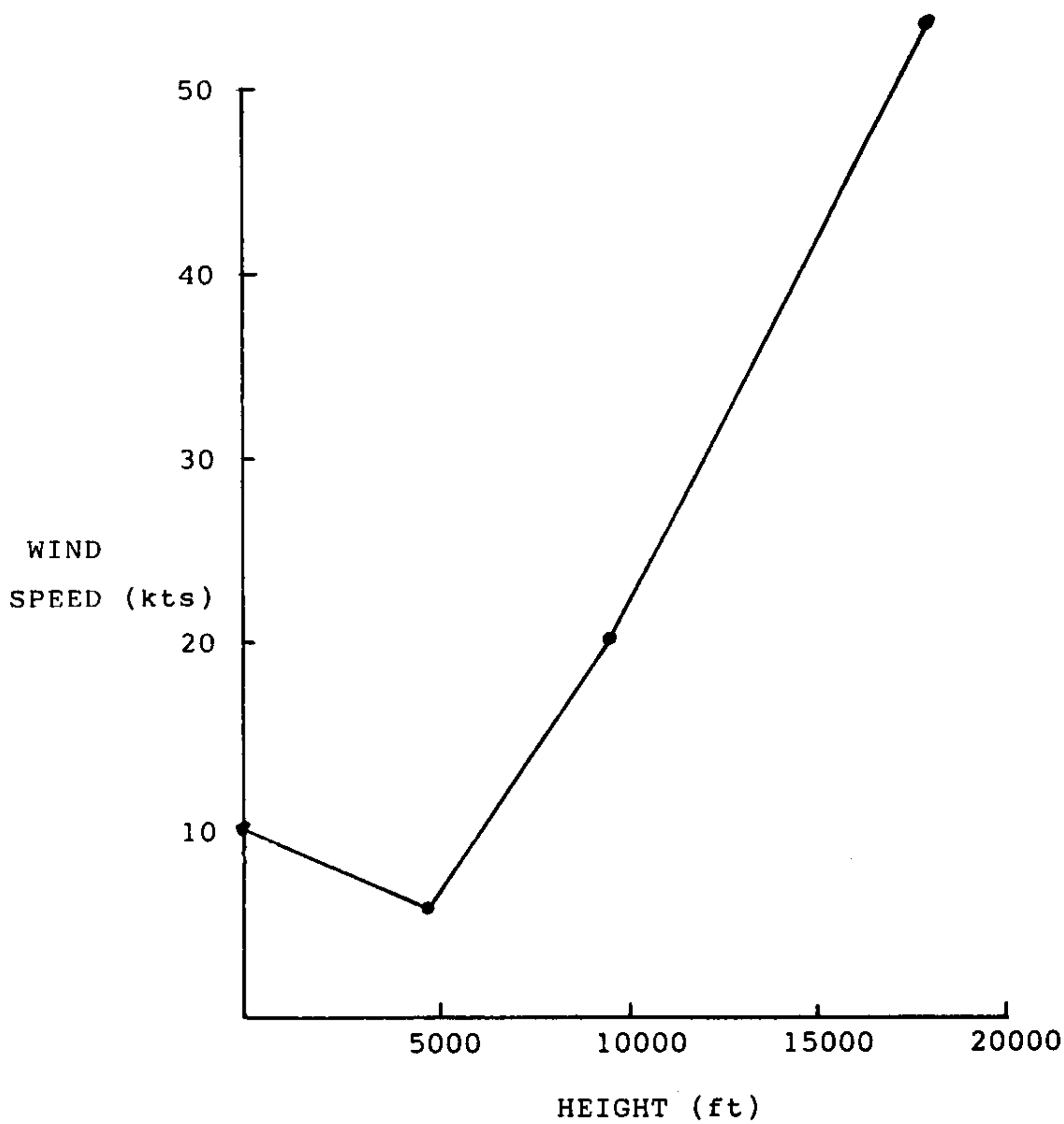

Figure 8. Wind speed as a function of height for the Quillayute, WA radiosonde sounding for 00 GMT March 7, 1991.

175° between 00 GMT and 01 GMT March 7th. Similarly, the wind direction at Seattle changed from 150° to 300° during these hours. With relatively light predicted and observed surface wind speeds and substantial variations in observed wind directions, it appeared that the errors in the model winds for most stations were generally not significant.

The observed precipitation for the 24 hour period ending at 12 GMT March 7th and the corresponding model generated precipitation are given in Table 3. The model was run for 5 hours with no synoptic precipitation. The model reproduced the nearly 1 inch of precipitation that fell at Paradise on Mt. Rainier while most other stations received .1 inches or less. The model did less well for Mt Hood Meadows and Government Camp, both in the Mt. Hood area. Observed precipitation for these stations measured .20 and .34 inches whereas the model generated less than .1 inches. At Mt. Hood Meadows, the model's surface winds, which did not match the observed winds, account for the error. The model winds diverged and were downslope, which produced a negative vertical velocity. Although an upslope surface wind at Government Camp dominated the vertical velocity calculation, it was too weak to produce precipitation to match the observation.

The Northwest Avalanche Center (NWAC) provides quantitative precipitation forecasts (QPF) which cover a 24 hour period and are issued 48 hours and 24 hours prior to verification. The Avalanche Center QPF's for 9 stations are listed in Table 3. The QPF's are based on 48 hour and 24 hour prognoses, whereas the precipitation model was run on analysis data. However, comparing the gridded data for the 850 mb level 24 hour prognosis from the 00 GMT March 6 NGM run to the 00 GMT March 7 analysis, the northwest flow over the model's domain is very similar, with the amplitude of the ridge slightly greater than forecast and the 850 mb level temperatures slightly lower than forecast. The model predicted precipitation is substantially more accurate for this case than were the NWAC forecasts. This is particularly apparent for Paradise, where observed precipitation was nearly three times heavier than for any other station. The model duplicated Paradise's anomalously high precipitation. In contrast, the NWAC forecast 1/4 of the observed precipitation and grouped Paradise with other stations that typically receive relatively heavy precipitation, ie, Mt. Baker, Stevens Pass and Snoqualmie Pass.

CASE 2: 00 GMT MARCH 12, 1991, MOIST SOUTHWESTERLY FLOW

At 00 GMT March 12th, the upper level flow was characterized by a trof of low pressure centered off the west coast along 135°W longitude with a moist southwesterly flow moving through Oregon and Washington. A weak upper

TABLE 3 Observed (OBS) and model (MODEL) predicted precipitation for 19 sites in western Washington and Oregon for 00 GMT March 7, 1991. Northwest Avalanche Center 24 hour quantitative precipitation forecasts for 9 sites issued 48 (2-DAY FX) and 24 (1-DAY FX) hours before verification at 00 GMT March 7.

STATION NAME	OBS PRECIP	MODEL PRECIP	2-DAY FX	1-DAY FX
Mt Baker	0.00"	0.00"	.25-.5"	.25"
Stevens Pass	0.00"	0.06"	.25-.5"	.25-.5"
Mission Ridge	0.00"	0.12"	<.25"	<.25"
Snoqualmie Pass	0.00"	0.00"	.5"	.25-.5"
Crystal Mountain	0.01"	0.08"	.5"	<.25"
Paradise/Mt. Rainier	0.95"	0.98"	.5"	.25"
White Pass	0.00"	0.07"	.25"	<.25"
Mt. Hood Meadows	0.20"	0.00"	.5"	<.25"
Government Camp	0.34"	0.09"	.5"	<.25"
Stampede Pass	0.10"	0.01"		
Quillayute	0.04"	0.03"		
Astoria	0.13"	0.02"		
Bellingham	0.00"	0.02"		
Seattle	0.00"	0.00"		
Tacoma	0.01"	0.04"		
Olympia	0.03"	0.09"		
Portland	0.09"	0.05"		
Wenatchee	0.00"	0.00"		
Yakima	0.00"	0.00"		

level ridge existed along 120°W longitude primarily in Oregon and California. The 850 mb analysis (Fig. 9) shows a closed low over and west of Vancouver Island with a trof extending south from the low along 130°W longitude. Quillayute had 30 kt southwesterly winds at 850 mb, while Salem measured 55 kt southwesterly winds. The Quillayute sounding had a nearly saturated adiabatic lapse rate from the surface to 600 mb (Fig. 10).

The imposed large scale wind field taken from the Quillayute sounding is shown in Figure 11. 25 kt or greater winds occured at all levels above the surface, with the winds at the 850 mb level stronger than those at 700 mbs.

The Mass-Dempsey wind model surface winds for 00 GMT March 12th are compared to the corresponding observed surface winds in Table 4. For most stations, the observed surface wind directions and speeds compare favorably with the model's winds; however, there are some notable exceptions. Crystal Mountain's observed winds were westerly 25 kts, compared to the model's SE 14 kts. This discrepancy may exist because the model winds are calculated for a grid point at the base of the ski area, whereas the observed winds are measured at the top of the ski area on a 2100 m ridgetop. Paradise at Mt. Rainier is more difficult to explain. The model predicted E winds 15 kts while Paradise recorded light variable winds. The wind instruments at

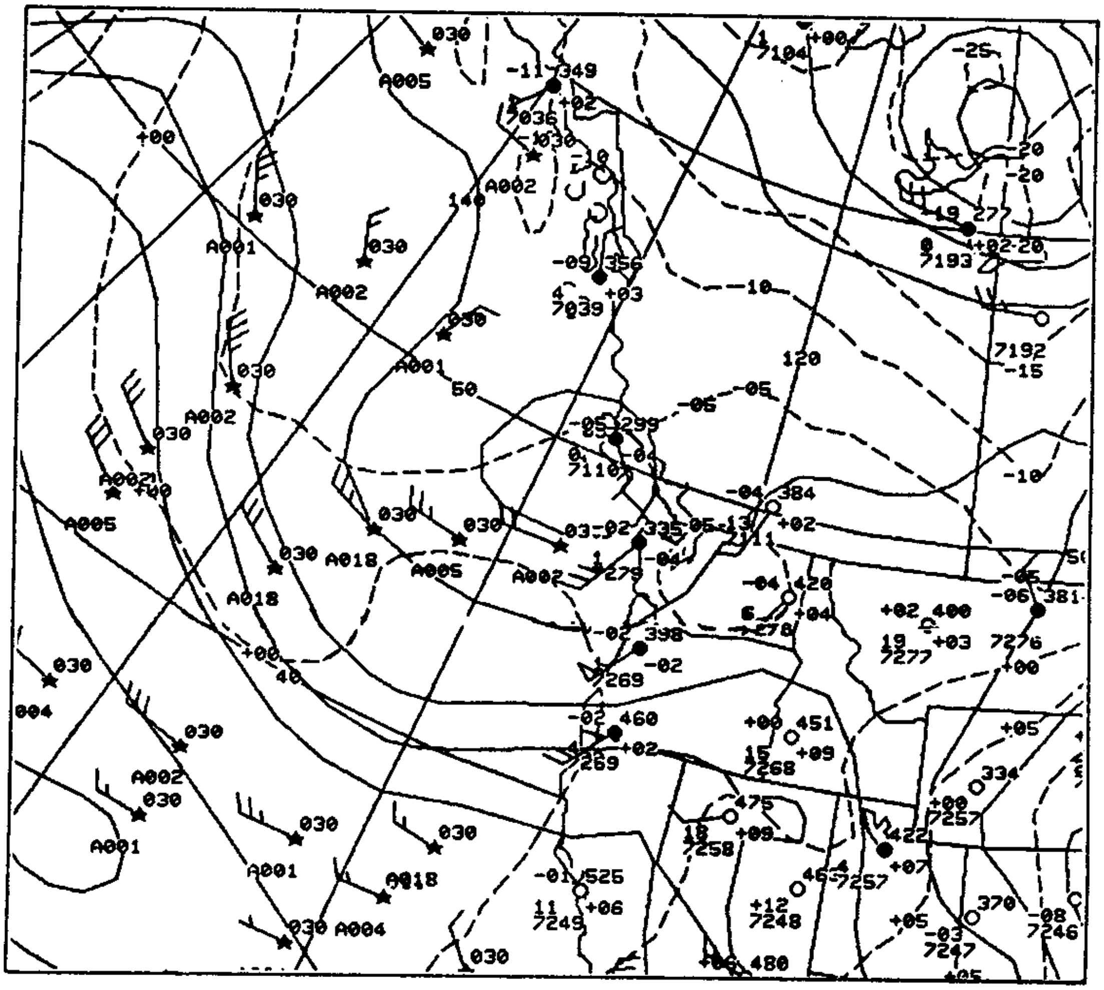

Figure 9. NMC 850 mb height and temperature analysis for 00 GMT March 12, 1991. Height contours (solid lines) are drawn at 30 m intervals and are labeled in tens of meters; temperature contours (dashed lines) are labeled in degrees Celsius.

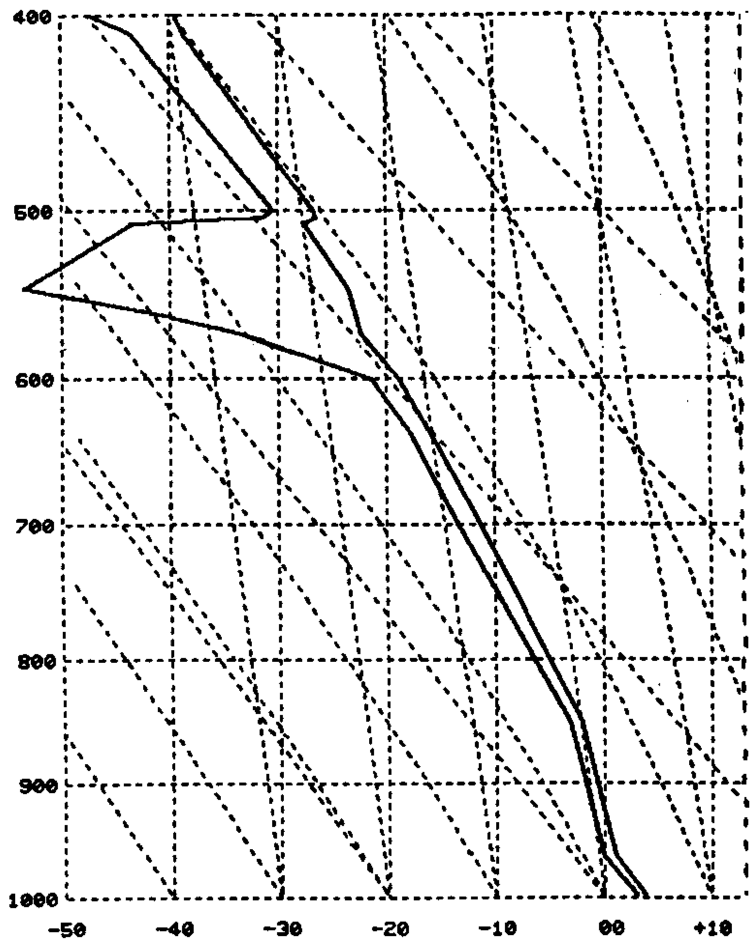

Figure 10. Quillayute, Washington radiosonde sounding for 00 GMT March 12, 1991.

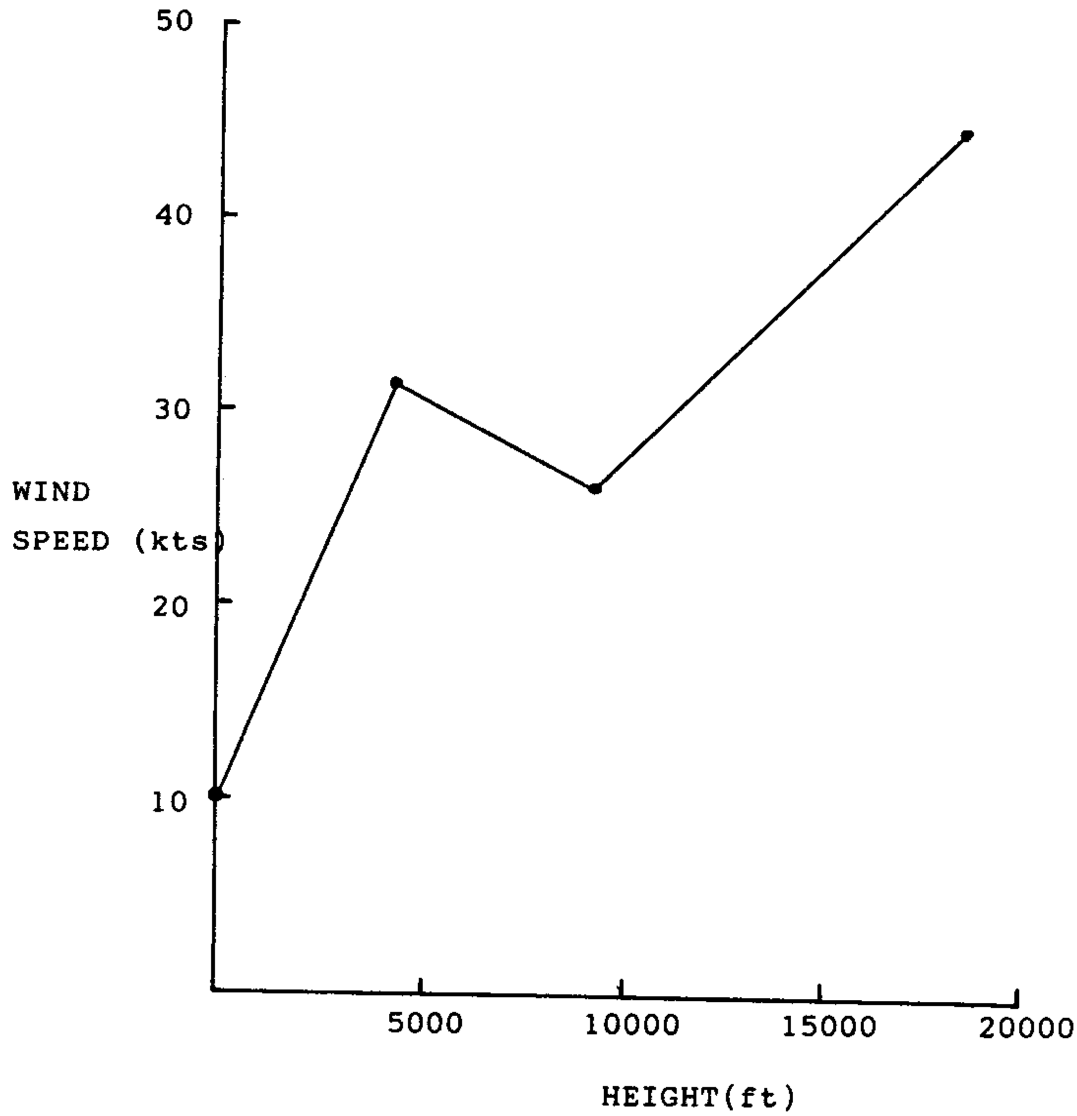

Figure 11. Wind speed as a function of height for the Quillayute, WA radiosonde sounding for 00 GMT March 12, 1991.

TABLE 4 Observed and model predicted surface winds for 14 sites in western Washington and Oregon for 00 GMT March 12, 1991

STATION NAME	OBSERVED WINDS	PREDICTED WINDS
Stevens Pass	103° 14 kts	110° 17 kts
Mission Ridge	229° 13 kts	144° 13 kts
Snoqualmie Pass	90° 13 kts	114° 16 kts
Stampede Pass	80° 10 kts	127° 14 kts
Crystal Mountain	272° 25 kts	135° 14 kts
Paradise/Mt. Rainier	var 2 kts	70° 15 kts
Mt. Hood Meadows	242° 19 kts	136° 17 kts
Government Camp	175° 10 kts	129° 12 kts
Quillayute	160° 8 kts	152° 24 kts
Astoria	160° 11 kts	142° 17 kts
Bellingham	130° 9 kts	133° 18 kts
Seattle	130° 10 kts	110° 17 kts
Olympia	200° 13 kts	162° 12 kts
Yakima	110° 10 kts	128° 9 kts

Paradise have had riming problems this winter, which may have been the case on this date. The model generally overpredicted wind speeds along the coast, especially at Quillayute where model winds were 16 kts greater than observed winds. Although Quillayute is located 6 km inland, the model's 7.5 km grid effectively makes it a coastal station.

Model generated and observed precipitation for the 24 hour period ending at 12 GMT March 12th are compared in Table 5. The precipitation model was run for 6 hours with a .04"/hr synoptic precipitation rate. For most stations, model and observed precipitation compare favorably, with the model essentially duplicating the precipitation that fell at the following stations: 1.58" at Paradise, .52" at Snoqualmie Pass, .33" at Mt Baker Ski Area and .28" at Olympia.

Significant differences occur in the Mt. Hood area where Mt. Hood Meadows and Government Camp measured .98 and .87 inches of precipitation respectively, whereas the model only generated .18 and .53 inches. Two factors may explain this discrepancy. First, the imposed wind field is derived from the Quillayute sounding; however, in this case, the 850 mb level winds from the Salem sounding were significantly stronger than Quillayute's 850 mb winds (55 kts/32 kts). Had Salem's winds been used for the imposed wind field in

TABLE 5 Observed (OBS) and model (MODEL) predicted precipitation for 18 sites in western Washington and Oregon for 00 GMT March 12, 1991. Northwest Avalanche Center 24 hour quantitative precipitation forecasts for 9 sites issued 48 (2-DAY FX) and 24 (1-DAY FX) hours before verification at 00 GMT March 12.

STATION NAME	OBS PRECIP	MODEL PRECIP	2-DAY FX	1-DAY FX
Mt Baker	0.33"	0.31"	.5-.75"	.5"
Stevens Pass	0.43"	0.54"	.5-.75"	.25-.5"
Snoqualmie Pass	0.52"	0.56"	.5-.75"	.5-.75"
Crystal Mountain	0.67"	0.49"	.5"	.25-.5"
Paradise/Mt. Rainier	1.58"	1.58"	.75-1.0"	.75"
White Pass	0.41"	0.30"	.25-.5"	.25-.5"
Mt. Hood Meadows	0.98"	0.18"	.75"	.25-.5"
Government Camp	0.87"	0.53"	.75"	.25-.5"
Stampede Pass	0.73"	0.42"		
Quillayute	0.44"	0.27"		
Astoria	1.17"	0.29"		
Bellingham	0.32"	0.24"		
Seattle	0.45"	0.28"		
Tacoma	0.43"	0.29"		
Olympia	0.28"	0.36"		
Portland	0.19"	0.46"		
Wenatchee	0.00"	0.21"		
Yakima	0.00"	0.18"		

the south, the Mt. Hood area would have received substantially more precipitation. Second, the model surface winds at Mt. Hood Meadows were southeast 17 kts. For this wind direction, the terrain produced a strongly negative vertical velocity which factored significantly in the total vertical velocity calculation. The observed winds at Mt Hood Meadows measured southwest 22 kts. Southwest winds would have produced strong positive vertical velocities which would have resulted in a more accurate precipitation forecast.

The model also underpredicted precipitation along the Pacific coast, especially at Astoria where measured precipitation was 1.17 inches compared with the model's .29 inches. This is a consistent problem with the precipitation model. The Mass-Dempsey wind model produces frictional convergence along the coast as the airflow moves from water onto land. At Astoria, the total vertical velocity for this case results almost exclusively from convergence (97%); however, the magnitude is still insufficient to account for the relatively heavy precipitation that often falls at coastal stations.

The model overestimated precipitation at Yakima and Wenatchee in spite of decreasing the moisture available for condensation by 67%. Although Yakima's surface winds were only 9 kts from the southeast, the terrain configuration produced upslope winds for both the southeast surface winds and the southwest imposed wind field winds, as well as converging surface winds in the Yakima River valley, thus, all three vertical velocity components were positive for this case. The imposed wind field wind (SW 20 kts) accounted for 42% of the total vertical velocity. It may be unrealistic to use the Quillayute sounding to imply large scale winds this far from the coast. Including Spokane's sounding to determine the imposed large scale wind field may improve model results.

The precipitation model was rerun on a small-scale terrain grid that measures 1.9 km on a side and extends from 47° to 48° N latitude and from 120.4° to 122.4° W longitude. The small scale terrain allows a more detailed analysis of precipitation patterns for highway maintenance and avalanche control along Interstate 90 from 5 km west of North Bend to Cle Elum and along Route 2 from Baring to Leavenworth.

Output for the March 12, 1991 case for I-90 over Snaoqualmie Pass is given in Figure 12a. Data is plotted at 5km intervals from west of North Bend to Cle Elum. Corresponding model terrain is shown in Figure 12b. The only point along the highway corridor currently available to verify model output is at Snoqualmie Pass, where observed precipitation was .52". Model calculated precipitation from the fine scale terrain was .49". This value differed from

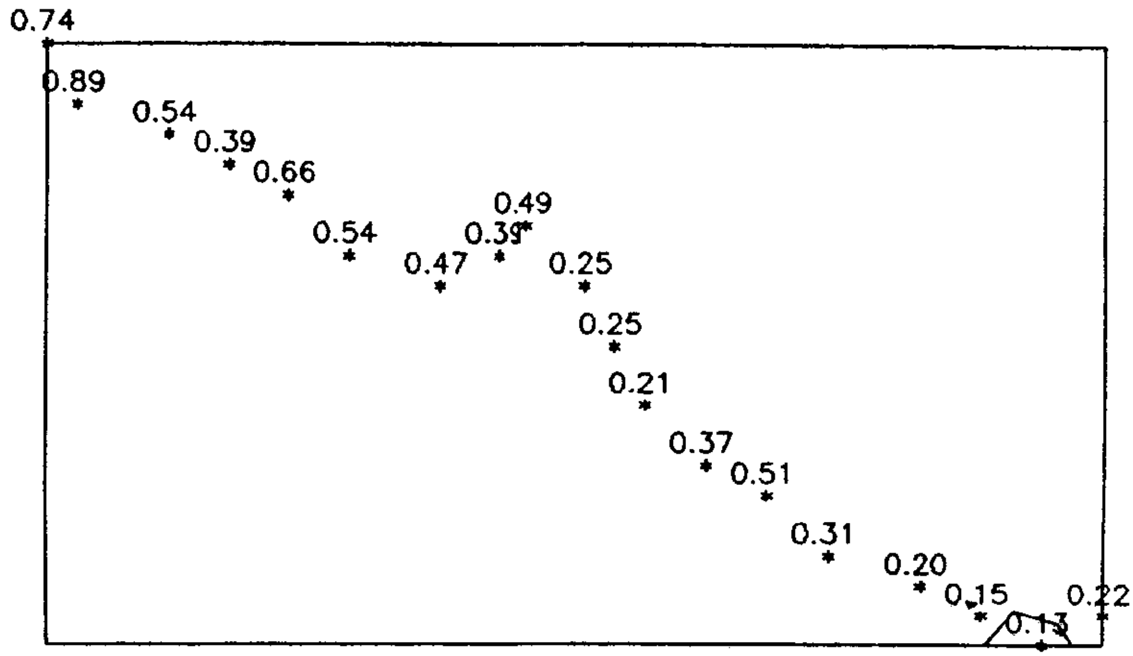

Figure 12a. Model predicted precipitation for the Interstate 90 Snoqualmie Pass highway corridor for 00 GMT March 12, 1991. Precipitation quantities are plotted at 5 km intervals from 5 km west of North Bend to Cle Elum. Precipitation quantities are in inches.

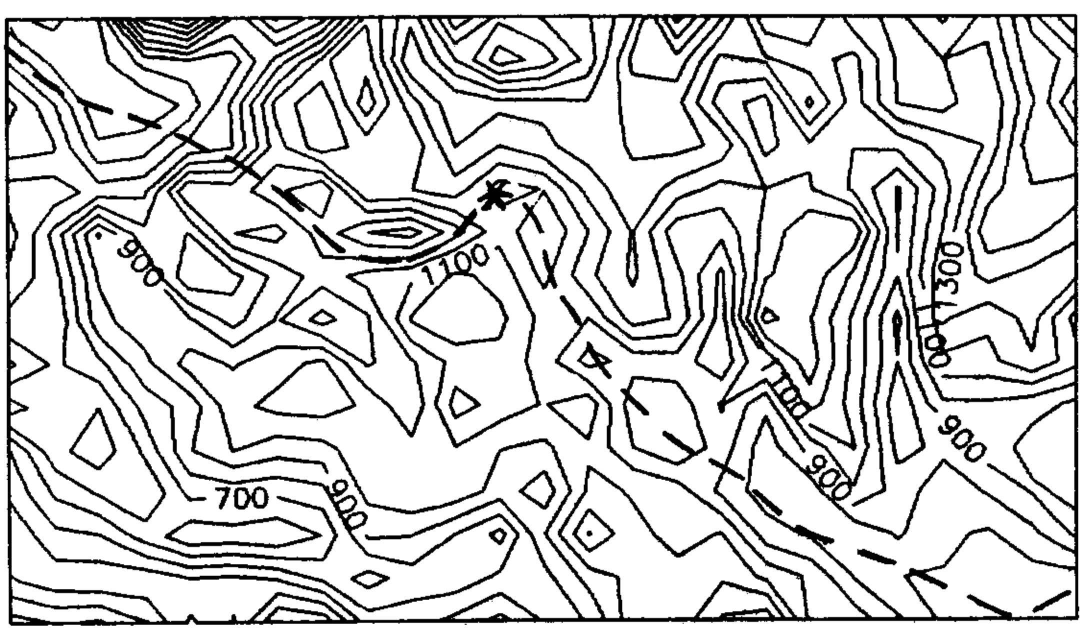

Figure 12b. Precipitation model run small scale topography for the area shown in Figure 12a. Heights are in meters. The contour interval equals 100 meters. The interstate highway corridor is indicated with a heavy dashed line. Snoqualmie Pass is marked with an X.

the precipitation based on the 7.5 km terrain grid (.56"). This discrepency results from the calculation for the slope induced surface wind vertical velocity. The fine scale terrain grid smoothes topographic features less than the 7.5 km terrain grid. It therefore produces more pronounced positive and negative vertical velocities and results in more widely varying precipitation quantities.

The precipitation values for I-90 in Figure 12a look reasonable if they are analyzed in conjunction with the terrain in Figure 12b. The relatively heavy precipitation quantities near North Bend (.74" and .89") result from a generally southwesterly flow being forced up steep terrain downwind. East of the pass there is an anomalously high precipitation value of .51". This grid point is also located upwind of relatively steep terrain.

The Northwest Avalanche Center (NWAC) quantitative precipitation forecasts for the 24 hours incorporating the 00 GMT model run are given in Table 5. The precipitation model outperformed the NWAC forcast for most stations. However, the NWAC forecast was based on 48 and 24 hour prognoses, whereas the precipitation model was run on analysis data. The 850 mb level 24 hour prognosis from the 00 GMT March 11th NGM model run and the 00 GMT March 12th analysis were similar, both exhibiting a general southwesterly flow. However, the 24 hour prognosis indicated a more pronounced trof along the northwest coast whereas the analysis had more tightly packed height contours. The precipitation model gave considerably more relative variation than did the Avalanche Center forecast, although for all but the Mt Hood area, both the model and the forecaster trends were similar and correct. Most station observations fit into the NWAC forecast categories, with Paradise given the heaviest relative forecast, even if the quantity was not correct. The model and the NWAC substantially underforecast precipitation in the Mt Hood area. As discussed earlier, the strong low level jet in the southern part of the domain may account for these discrepancies.

CLIMATOLOGY SIMULATION: MARCH 7 - MARCH 24 1991

The model was run for 00 GMT and 12 GMT analyses for the period from March 7th through March 24th. An attempt was made to run the model consecutively for the entire month of March; however, as a result of computer problems at the Northwest Avalanche Center, the required Quillayute and Salem sounding mandatory level files were lost from March 1st through March 6th. The model was run for the period from March 25th through March 31st; however, these runs were not included in the final summation for several reasons. The upper level flow at Quillayute was northeast on March 25th and 26th. Although precipitation did occur on these two days, precipitation with a northeast flow is unusual and the precipitation model parameterizations have not been written to account for winds from this quadrant. March 29th was the only other day after the 26th with precipitation. Although the precipitation model ran successfully, problems with the National Weather Service computer resulted in missing observations.

The days between March 7th and March 24th demonstrated a relatively wide range of weather conditions. Precipitation amounts from March 7th and 8th were highly variable and resulted from a moderate northwesterly flow. March 9th was dry. A moist southwesterly flow aloft characterized the 10th through 13th when most stations recieved moderate amounts of precipitation each day. The jet stream, which moved inland over British Columbia on the 10th sagged southward through the 13th. This trend is characterized by decreasing daily precipitation amounts at Mt. Baker and increasing amounts in the Mt. Hood area. A strong split in the upper level flow off the west coast resulted in little or no precipitation in the Pacific northwest from the 14th to the 18th. The only exception occured at Paradise on Mt Rainier which recieved .24" of water equivalent ending on the morning of the 15th. Precipitation increased again from the 19th through the 24th when the main storm track moved through California and the Pacific Northwest was under a southeast to southwest upper level flow.

Model generated precipitation for the period March 7 through March 24 is compared to observed precipitation totals in Table 6. 22 model runs produced precipitation. The model did very well for a number of stations, including Paradise on Mt. Rainier, White Pass and Olympia. As occured in Case 2, the model underestimated precipitation along the Pacific coast (Quillayute and Astoria) and overestimated precipitation at stations east of the Cascade crest (Yakima, Wenatchee and Mission Ridge).

Low elevation coastal stations have little if any vertical velocity contribution from the imposed geostrophic wind field. Those stations that are in addition surrounded by similar elevation terrain, ie, Astoria, rely primarily on surface wind convergence to produce model precipitation. Forecasters should expect the model to underestimate coastal precipitation, especially during moist south to southwest upper level flows. This is especially true for Astoria, where the wide mouth of the Columbia River results in sea level elevations downwind of the town.

Although the overestimates east of the Cascade crest appear significant, the total error involved ranges from .23" to .55", which averages out to .01"-.02" errors for each model run.

TABLE 6 Total observed and model predicted precipitation for 19 sites in western Washington and Oregon for the period from March 7 through March 24 1991

STATION NAME	TOTAL OBSERVED PRECIPITATION	TOTAL PREDICTED PRECIPITATION
Mt Baker	2.29"	1.60"
Stevens Pass	1.11"	1.67"
Mission Ridge	0.55"	0.78"
Snoqualmie Pass	2.30"	1.48"
Stampede Pass	2.78"	1.46"
Crystal Mountain	2.70"	0.81"
Paradise/Mt. Rainier	6.83"	7.01"
White Pass	1.42"	1.38"
Mt. Hood Meadows	2.21"	3.97"
Government Camp	3.01"	3.81"
Quillayute	2.59"	1.55"
Astoria	2.65"	1.27"
Bellingham	1.19"	0.97"
Seattle	1.35"	0.90"
Tacoma	1.64"	1.10"
Olympia	1.46"	1.41"
Portland	2.41"	1.45"
Wenatchee	0.20"	0.75"
Yakima	0.25"	0.60"

Errors at other stations are more difficult to generalize. The model overforecast precipitation in the Mt Hood area, but this is not reliably the case. When errors are analyzed for specific wind directions, the largest and most inconsistent variations in model versus observed precipitation occur during southwest upper level winds. However, close examination of the model terrain does not indicate why this should be the case.

The model underforecasts precipitation for Mt. Baker Ski Area. This may result because the ski area is located on Ptarmigan Ridge, which extends northeast from the mountain and is at a higher elevation than any of the terrain directly north, east or south of it. As a result, the vertical velocity calculation produces negative values for all of the most common precipitation producing large scale wind directions, ie, south through northwest. Model precipitation for Glacier, a low elevation station in the Nooksack River valley west of Mt Baker, often better reproduces the ski areas observed precipitation. Although Glacier is not included in this climatology summary, model output for Glacier is being printed out at the NWAC.

The model did least well for Crystal Mountain Ski Area. It tended to produce insufficient precipitation for southeast through southwest wind directions. The ski area is located at relatively high elevation at the southern end of a steep sided north-south oriented valley. As a result, terrain induced vertical velocites are negative for southerly winds and only weakly positive for southeast or southwest winds. The problems with forecasting precipitation quantities for Crystal Mountain are more complex than a simple terrain analysis can answer. Forecasters at the NWAC have struggled with understanding Crystal Mountain's precipitation for over 10 years. It often recieves very light amounts of precipitation compared to other Cascade sites, presumably as a result of rain shadowing by Mt Rainier, 20 km to its southwest. However, Crystal may receive substantially more precipitation than most Cascade sites, including Paradise on Mt Rainier, as was the case on both March 13th and March 22nd. It has been suggested that under certain atmospheric conditions, Crystal may be located under a convergence zone that forms downwind of Mt Rainier. For these two cases, the Quillayute sounding 700 mb level winds were both 220° at 15 and 21 kts. Many more cases need to be evaluated before any generalizations can be made.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

An orographic precipitation model originally developed on a main frame computer and presented in the Washington State Department of Transportation report number WA-RD 91.1 was adapted to run on an operational basis at the Northwest Avalanche Center in Seattle. Numerous improvements were made to the model's precipitation parameterizations based on model verification during the 1989-90 and 1990-91 winter seasons.

The precipitation model assumes that precipitation is directly proportional to the vertical velocity generated by the interaction of a wind field and topography. Surface wind data from the Mass and Dempsey (1) wind model is used to calculate a slope induced vertical velocity and convergence induced vertical velocity. Because momentum from upper levels in the atmosphere is felt at higher elevations, a separate wind field representing the large scale flow is imposed on the model terrain. The imposed wind field's direction is held constant over the model's domain while the wind speed varies with height. The wind speed profile and wind direction are taken from the Quillayute sounding for model runs based on National Meteorological Center (NMC) analysis data and from the Nested Grid Model gridded data near Quillayute for model runs using NMC prognosis data. A simple precipitation parameterization scheme is employed where the amount of condensation is proportional to vertical velocity. The moisture available for condensation is varied linearly north to south depending on the saturated mixing ratios at Quillayute and Salem for analysis runs and at Vancouver, B.C., Seattle, WA and Portland, OR for prognosis runs. Based on the dew point depressions at the above sites, the airmass at each grid point is assigned saturation parameters. It is then lifted dry adiabatically until it reaches saturation, at which point condensation progresses. For south through north-northwest wind directions, where the Cascades act as an efficient moisture barrier, the saturated mixing ratio is decreased by 67% from the western Cascade foothills to eastern Washington. Refer to Figure 3 for complete details of the moisture depletion function. A constant condensation to precipitation efficiency is assumed with the remaining condensate carried to the next grid point downstream.

Two case studies were presented. The first case was characterized by a north-northwesterly large scale flow and showery precipitation with observed precipitation quantities for March 7 varying from .95" at Paradise on Mt Rainier to less than .1" at most other stations. The model duplicated the precipitation at 19 sites fairly well; however, the model underpredicted precipitation in the Mt Hood area. The model's southeast winds did not match the observed southwest winds, which may account for the precipitation discrepancy. The wind model tends to produce southeast surface winds along the length of the Cascade crest during a southwesterly flow aloft. East or southeast winds are realistic for most of the low elevation passes; however, the observed wind direction generally resembles the large scale wind direction 400-700 vertical meters above pass level. Mount Hood's proximity to the Columbia River Gorge may account for the model's consistent tendency toward southeast winds.

The second case had a moist southwesterly large scale flow. The model reproduced observed precipitation for many of the stations including Paradise, Snoqualmie Pass, Mt Baker Ski Area and Olympia. The model underpredicted precipitation along the Pacific Coast. Several factors may account for the underprediction, which is a consistent problem with model output. Low elevation coastal stations, which experience negligible vertical velocity from the imposed large-scale wind field, rely primarily on convergence induced vertical velocity to generate condensation. Although the Mass-Dempsey wind model does produce frictional convergence along the coast as air flows from the ocean onto land, the magnitude is generally insufficient to account for the relatively heavy precipitation that often falls at coastal stations. Model precipitation for Astoria is particularly light during south or southwest winds. This occurs because Astoria, at sea level on the south side of the mouth of the Columbia River, gets no slope induced upward vertical velocity from either surface winds or the imposed large-scale winds, and must therefore rely exclusively on convergence to generate condensation.

Model accuracy was compared to the Northwest Avalanche Center (NWAC) quantitative precipitation forecast (QPF) verifications for 9 stations in the Washington and Northern Oregon Cascades. The model was run on 0 hour products, whereas the NWAC forecasters were using 24 and 36 hour model output; however, for the two cases studied the prognoses were very similar to the corresponding analysis. For both cases, the model better reproduced observed precipitation quantities than did the NWAC forecast. Although the relative trends of the NWAC forecasts were correct, the QPF's were all grouped within a fairly narrow range. In contrast, the observed precipitation quantities demonstrated a wide spread as did the model.

The model was run at 12 hour intervals from March 7 through March 24, 1991. Total model precipitation for the period was compared to observed totals to test the models ability to reproduce climatology. The model did very well at Paradise, White Pass and Olympia. The model underpredicted precipitation along the Pacific coast; as explained in the preceding paragraph. East of the Cascade crest, the model overpredicted precipitation; however, the average error for each model run was only .01" to .02".

In conclusion, the precipitation model does very well considering the simple precipitation parameterizations that are employed. Most of the significant deviations from observations can either be attributed to errors in the wind model or can be anticipated by a forecaster familiar with the model's consistent errors. The precipitation model should provide forecasters with useful guidance during flow patterns that exhibit relatively two-dimensional characteristics. Although it is not expected to do well for situations with significant three-dimensional structure, the model may still be a useful predictive tool for sites like Paradise on Mt Rainier, which are high enough to be influenced largely by the upper level flow, as was the situation in case 2.

RECOMMENDATIONS

If time or funding allowed, further improvements could be made to the precipitation model. The wind speed and direction from Quillayute is used for the imposed large-scale wind field. As occured in case 2 on March 12th, the upper level wind speeds at Salem may differ significantly from those at Quillayute. It would be relatively simple to vary the imposed wind field's vertical profile from north to south through the model's domain based on the Quillayute and Salem radiosonde wind profiles. More realistic winds for eastern Washington could be obtained by including the Spokane radiosonde vertical wind profile as well.

The moisture field is varied linearly north to south using data from the Quillayute and Salem soundings for model runs based on NMC analyses. The inclusion of the Port Hardy sounding data would give further detail to the moisture field.

Currently, the precipitation model is run either for an 'orographic' flow, in which case the large scale wind vector is located 3.75 km inside the upwind terrain boundary, or for a 'convective' pattern, where the large scale wind vector is centered in the terrain grid. A combination of these dynamics often occurs. The model could be organized to allow a forecaster to assign proportions to the amount of convective versus orographic lifting expected.

At present, fine scale precipitation output is generated for the Stevens Pass and Snoqualmie Pass highway corridors to help with maintenance and for a 22 km area centered on each pass to help with avalanche control. It may be useful to highway maintenance and avalanche control personnel to provide detailed precipitation model output for the North Cascades Highway, Highway 542 below Mt. Baker Ski Area, Highway 410 over Chinook Pass, the Crystal Mountain Boulevard and Highway 12 over White Pass.

Forecasters at the Northwest Avalanche Center have requested that a detailed user manual be written that would help interpret model results for specific stations and for a variety of weather situations. While a complete analysis of individual station precipitation and winds would be required to produce a manual, such analyses would provide useful operational tools to aid in model interpretation and quantitative precipitation forecasts.

IMPLEMENTATION

The object of this research was to implement an earlier research project (Report WA-RD-91.1). An orographic precipitation model previously developed on a main frame computer and organized to run for research purposes was transferred to a personal computer and is being used operationally at the Northwest Avalanche Center. Numerous improvements were made to the precipitation parameterizations used in the model. Although further improvements could undoubtedly be made, model output is useful to forecasters and model accuracy falls within the range of expectations for a simple two-dimensional precipitation model.

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Dave Dempsey and Cliff Mass developed and supplied the wind model which served as a foundation for the precipitation model.

Mark Moore, Sue Ferguson and Kenny Kramer from the Northwest Avalanche Center patiently ran and reran many versions of the precipitation model and made numerous thoughtful suggestions for improving the model.

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APPENDIX A: SYMBOLS USED IN MODEL EQUATIONS

SYMBOL	DEFINITION
c	condensation
c_p	specific heat of dry air at constant pressure
D	depth of lifted airmass (1500 m)
dh/dx	terrain slope in x-direction
dh/dy	terrain slope in y-direction
dqs/dz	change in the saturated mixing ratio with height
dx	distance between adjacent grid points in x -direction
dy	distance between adjacent grid points in y -direction
E1	condensation to precipitation efficiency (.5)
E2	condensation carrying efficiency (.75)
F	moisture depletion factor
$h_1 - h_4$	average heights of terrain grid points surrounding wind vector
L	latent heat of vaporization
p_s	synoptic precipitation term
p_T	precipitation calculated by model
R	condensate carried to next grid downwind
t	time
u	component of surface wind field in x-direction
u_{ls}	component of large scale wind field in x -direction
v	component of surface wind field in y-direction

APPENDIX A: (continued)

SYMBOL	DEFINITION
v_{LS}	component of large scale wind field in y -direction
w_{LS}	total vertical velocity from large scale wind field
w_{LSX}	slope induced vertical velocity from large scale wind field in x-direction
w_{LSY}	slope induced vertical velocity from large scale wind field in y-direction
ws	total slope induced vertical velocity from surface wind
wsx	slope induced vertical velocity from surface wind in x-direction
wsy	slope induced vertical velocity from surface wind in y-direction
w_{TOTAL}	total vertical velocity
$\partial w/\partial z$	vertical velocity at the surface from convergence
Γd	dry lapse rate
Γm	moist lapse rate