Mesoscale Numerical Simulation of the 1986 Sacramento Valley Flood Event

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Abstract

The University of California, Davis and Lawrence Livermore National Laboratory have recently developed a Mesoscale Atmospheric Simulation (MAS) model to study the airflow and precipitation over areas of complex terrain like those in California. The model includes parameterized physical processes for the explicit cloud microphysics (cloud, ice, rain, snow, and graupel), radiation, soil, surface, and boundary layer. This model employs a 3rd order accurate advection scheme designed by Takacks (1987) and Hsu and Arakawa (1990). This scheme preserves the peak value well and produces no phase error with little computational oscillations. The steep and complex topography over our area of interest will generate spurious numerical oscillations that need proper treatment.

The model has been used to simulate the case of 1986 Sacramento Valley flood between Feb. 11 to 22. The simulated maximum precipitation over northern Sierra is 52 inches, which differs from the observation by less than 2 inches. The simulation also demonstrated the capability of the model to predict surface hydrology such as the accumulated snow depth during the storm, which are crucial to the water supply in California.

1. Introduction

Accurate simulation of precipitation is an important part of numerical weather prediction. Precipitation processes are usually divided into two categories in numerical models: large-scale and convective precipitation. In the western United States, convective precipitation is important for summertime precipitation. Large-scale precipitation, however, is the most important in the western United States since most of the annual precipitation occurs during wintertime and is primarily due to stratocumulus clouds. As a result, proper representation of large-scale condensation is a crucial requirement for accurate simulation of wintertime precipitation in the western United States.

The large-scale condensation is treated with various levels of complexity in numerical models. The simplest and the most widely used one is the isobaric condensation scheme which assumes that whenever the water vapor mixing ratio within a grid box exceeds a threshold value, the excess water vapor is condensed and a portion of condensed water (or ice) falls as precipitation. This scheme is simple and economical; however, the treatment of fall out and storage of condensed water is somewhat arbitrary. On the other hand, a parameterized cloud
microphysics, that has been widely used in cloud models, is so far the most physically-based scheme used to compute large-scale condensation in numerical models. Zhang et al. (1988) and Giorgi (1991) reported that use of explicit microphysics has significantly improved simulated storm structures and precipitation compared to isobaric condensation scheme.

In the following, we will briefly present the formulation and important physical processes included in the model. Results of the case study and discussions will follow in subsequent sections.

2. Model description

The MAS model is a primitive-equation, limited-area model intended primarily to simulate meso-β scale features. The governing equations are the flux-form of the primitive equation written on σ-coordinates (e.g., Anthes and Warner 1978):

\[
\begin{align*}
\frac{\partial (\pi u)}{\partial t} &= -m^2 \left[ \frac{\partial \left( \pi u \right)}{\partial x} + \frac{\partial \left( \pi v \right)}{\partial y} \right] + \eta f - \frac{\partial (\pi \phi)}{\partial \sigma} - m \left( \frac{\partial \phi}{\partial x} - \sigma \frac{\partial \phi}{\partial \sigma} \right) + \pi F_x \\
\frac{\partial (\pi v)}{\partial t} &= -m^2 \left[ \frac{\partial \left( \pi u \right)}{\partial x} + \frac{\partial \left( \pi v \right)}{\partial y} \right] - \eta f - \frac{\partial (\pi \phi)}{\partial \sigma} - m \left( \frac{\partial \phi}{\partial y} - \sigma \frac{\partial \phi}{\partial \sigma} \right) + \pi F_y \\
\frac{\partial \phi}{\partial t} &= -C_p \partial \pi \partial P \\
\frac{\partial (\pi \theta)}{\partial t} &= -m^2 \left[ \frac{\partial \left( \pi u \right)}{\partial x} + \frac{\partial \left( \pi v \right)}{\partial y} \right] - \frac{\partial (\pi \phi \theta)}{\partial \sigma} + \pi Q \\
\frac{\partial (\pi q)}{\partial t} &= -m^2 \left[ \frac{\partial \left( \pi u \right)}{\partial x} + \frac{\partial \left( \pi v \right)}{\partial y} \right] - \frac{\partial (\pi \phi q)}{\partial \sigma} + \pi S \\
\frac{\partial \pi}{\partial t} &= -m^2 \left[ \frac{\partial \left( \pi u \right)}{\partial x} + \frac{\partial \left( \pi v \right)}{\partial y} \right] - \frac{\partial (\pi \phi)}{\partial \sigma} 
\end{align*}
\]

where \( m \) is the map factor, \( \pi = \pi_\text{ek} - \pi_\text{top} \), \( P = (p / p_0)^{\gamma / c_p} \), \( Q \) the diabatic heating rate, and \( S \) is the net source term for a variable \( q \) which is an active or passive tracer (water vapor or other pollutants), and \( F_x \) and \( F_y \) are non-conservative forcing on the \( x \)- and \( y \)-component of momentum, respectively. Other symbols in Eqs. (1)-(6) have conventional meanings. The continuity equation (6) is integrated vertically to yield the surface pressure tendency equation (Arakawa and Suarez 1983):

\[
\frac{\partial \pi}{\partial t} = -m^2 \int_{\pi_\text{top}}^{\pi_\text{ek}} \left[ \frac{\partial (\pi u)}{\partial x} + \frac{\partial (\pi v)}{\partial y} \right] d\sigma
\]

The governing equations (1)-(7) are discretized on the \( \sigma \)-grid. To solve the flux form of the advection equation, we employ the third-order accurate finite-difference scheme by Takacaks (1987) and later modified by Hsu and Arakawa (1990). This finite-difference advection scheme is nearly positive-definite and causes minimal numerical dispersion or phase error. Except the advection part of governing equations, we employ forth-order accurate, centered finite difference scheme to compute horizontal differentiation of variables (e.g., computing
pressure gradient force) except at lateral boundaries where second order accurate scheme is used. The vertical differencing of variables follow the method introduced by Arakawa and Suarez (1983).

Precipitation processes are computed by a Kuo-type cumulus scheme and a parameterized microphysics by Cho and Iribarne (1987) for deep convection and grid-scale condensation, respectively. The cloud microphysics scheme includes interactions between the water vapor and five classes of hydrometeors (cloud water, cloud ice, rain, snow, and graupel).

The solar and terrestrial radiative transfer is computed using the multi-layer schemes by Davies (1982) and Harshvardhan and Corsetti (1984), respectively, after they are modified to include the effects of clouds. The shortwave radiative transfer scheme employs Delta-Eddington (two-stream) approximation for large (small) optical thickness. The longwave radiative transfer scheme is a bulk-type parameterization which computes emissivity in the presence of water vapor, ozone, and carbon dioxide. The effects of clouds in the short and longwave radiative transfer are computed by separately considering water and ice particles using the formulation by Stephens (1978) and Starr and Cox (1982), respectively. The cloud particle concentration is directly computed by the cloud microphysics scheme. We do not consider partial cloudiness, i.e., an entire grid box is either filled with clouds or cloud-free.

Vertical turbulent transfer of momentum, heat, and tracers at the surface is computed by the bulk aerodynamic transfer scheme (Deardorff 1978). Vertical turbulent transfer above the surface layer is computed using a K-theory where the eddy transfer coefficients are computed by a stability-dependent scheme by Louis et al. (1981).

Surface temperature and mixing ratio for computing surface fluxes are obtained from surface energy balance equation. To compute surface energy balance in a more physical way we employ a physically-based Coupled Atmosphere Plant Snow (CAPS) model developed at Oregon State University (Mahrt and Pan 1984; Ek and Mahrt 1991; Kim et al. 1994). This model predicts the soil temperature, soil water content, equivalent snow depth, and canopy water content. Overall surface evapotranspiration is computed separately for vegetated and bare soil surfaces.

3. Results

The observed total precipitation in California during the 12-day period is shown in Fig. 1. The heaviest precipitation is observed over the western slopes of the Sierra-Nevada and Coastal Range. Precipitation is light in the Central Valley and decreases toward the southern California. The daily precipitation varies closely with the large scale water vapor convergence as heavy precipitation events occur during the periods of strong large scale water vapor convergence in the region (Fig. 2).
Fig. 1 Total precipitation (rain and snow: inches) observed during the 12-day period.

Fig. 2 Daily precipitation averaged over 165 stations in California (open circles) and the water vapor flux convergence across the model domain derived from NMC analysis.

The simulation is initialized using the NMC analysis at 00Z Feb. 11 1986. We update the lateral boundary conditions for every 12 hour intervals to represent the time-dependent large scale flow during the simulation. The domain of 1140 km x 1260 km covers much of the state of California, Nevada, and southern Oregon. This domain is divided with 20 km x 20 km grid mesh and fourteen vertical layers. The top of the model domain is located at 50 mb level. At this resolution, the topography of the model domain (Fig. 3), that is characterized by two major mountain ranges, the Coastal Range and Sierra-Nevada Mountains, with the
Central Valley between these mountain ranges, is well represented.

**Model Topography (m)**

[Model Topography Image]

Simulated 12-day accumulated precipitation (Fig. 4) agrees well with the observation. It clearly reflects the orographic effects on the local precipitation. The location and magnitude of the observed precipitation maxima at the western slope of the northern Sierra-Nevada is well reproduced in the simulation. Fig. 5 shows the daily precipitation averaged over 165 stations within California (circles) and over the model grids that contain at least one of those stations (solid line). The simulated daily precipitation, again, agrees closely with the observation.

Inclusion of an explicit microphysics in the model plays an important role in modeling the precipitation. Much of the precipitation in the valley and at the eastern slope of the Sierra-Nevada appears is due to the precipitating particles, especially snow, formed over the Coastal Range and Sierra-Nevada and transported downstream. Without including an explicit microphysics, it is impossible to distinguish the different fall speeds of rain and snow. Another advantage of using an explicit microphysics is that we can predict rainfall and snowfall separately (Fig. 6).
The CAPS model computes snow accumulation as the difference between the fresh snowfall and snowmelt. Since the amount of snow cover at the beginning of the simulation is not available, only the net accumulation during the simulated period is computed. The results (Fig. 7) show that most of the fresh snow on high lands of the Sierra-Nevada is added to the existing snow pack at the end of the simulated period. On the other hand, much of the fresh snow in the northern California has been melted. Since the snow pack over high lands is important for the summertime water supply in the western U. S., an accurate assessment of
snow cover at the end of the wet season is an important information for planning short- and long-term water supply for industries, environment, and urban areas.

**Total Rain: Control**

**Total Snow: Control**

Fig. 6 Simulated 12-day total rainfall (left) and snowfall (right). The units and contour levels are the same as in Fig. 4.

**12-day accumulated snow**

Fig. 7 Accumulated snow (cm) during the 12-day simulation period. Contour levels are the same as in fig. 4.
4. Conclusion

A twelve-day episode of heavy wintertime precipitation in the western United States is simulated using a mesoscale model nested within the NMC global analysis. Combination of a Kuo-type cumulus scheme with parameterized cloud microphysics successfully reproduced important features of the observed precipitation.

The observed and simulated precipitation shows that the local topography and large scale water vapor flux are the two major factors in the local precipitation. The cloud droplets and precipitating particles, especially snow, transported downstream out of the upslope regions of the major mountain ranges contributed to the most of the precipitation at the lee side of the major mountain ranges, including the Central Valley.

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