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Precipitation Structure in the Sierra Nevada of California During Winter

Ganesh R. Pandey, Daniel R. Cayan, and Kostantine P. Georgakakos
Climate Research Division, Scripps Institution of Oceanography
University of California, San Diego

ABSTRACT

The influences of upper air characteristics along the coast of California upon the winter time precipitation in the Sierra Nevada region were investigated. Most precipitation episodes in the Sierra are associated with moist southwesterly winds and also tend to occur when the 700- mb temperature is close to -2^0 C. This favored wind direction and temperature signifies the equal importance of moisture transport and orographic lifting for maximum precipitation frequency. Making use of this observation, simple linear models were formulated to quantify the precipitation totals observed at different sites as a function of moisture transport. The skill of the model is least for daily precipitation and increases with time scale of aggregation. In terms of incremental gain, the skill of the model is optimal for an aggregation period of 5-7 days, which is also the duration of the most frequent precipitation events in the Sierra. This indicates that upper air moisture transport at Oakland can be used to make reasonable estimates of the precipitation totals for most frequent events in the Sierra region.

1 Introduction

High elevation winter (November-April) precipitation is the major source of water for irrigation, power generation and water supply purposes in California, as in many other western States. Since this precipitation is mostly in the form of snow, it is amenable to Remote Sensing; its background to such an effort, this considers the spatial structure of winter precipitation over the Sierra Nevada mountains of California. In this region, episodes of heavy winter precipitation are less frequent but contribute a large fraction of the winter total precipitation (Cayan and Riddle, 1992). These heavy precipitation events increase the thickness of snow accumulations at high elevations and produce immediate runoff at lower elevations. Heavy precipitation combined with snowmelt may cause flooding in low lying areas. Thus there is a great interest in the amount and spatial distribution of winter precipitation in the Sierra Nevada mountains of California.

Throughout the western states, strong links have been reported between upper air conditions and regional hydrologic and climatic variables such as monthly or seasonal precipitation, seasonal temperature, time of snowmelt, and streamflows (Gleick ,1989; Redmond and Koch, 1991; Chen and

Cayan, 1994; Cayan et al.,1993; and others). Meanwhile, most floods in the Sierra Nevada region are caused by heavy precipitation lasting from hours to a few days (Weaver, 1962) and thus it is also important to examine the linkage between daily precipitation and upper air conditions. Considering its hydrologic importance, we examined historical observations of daily precipitation from a network of Sierra Nevada stations in relation to the upper air conditions in the region and upstream, even over the North Pacific. Factors such as the role of mid-tropospheric air characteristics (wind direction, velocity, humidity) and location of station (lee or wind side of mountain) are considered in determining daily precipitation events. Considering the strong seasonality of precipitation in California, attention is focused on the cool season, that is, early winter (November-January) and late winter (February-April). By utilizing the observed dependency of the precipitation totals on upper air characteristics, attempts are also made to quantify the at-site precipitation totals accumulated at different time scales using the upper air data.

2 Data

Daily observations of precipitation in the Sierra Nevada and upper-air soundings at Oakland for the period 1948 through early 1988 were analyzed in this study. Daily precipitation data for 191 Cooperative Observer (COOP) precipitation stations located between 35°N and 42°N in the Sierra Nevada range were obtained from NOAA. These COOP stations report total daily precipitation, snowfall depth and total depth of snow on the ground, as well as minimum and maximum temperatures, generally but not always at 18-hrs. The upper air sounding data from Oakland include the layer-mean temperature, pressure, relative humidity, wind speed and wind direction for 900- through 300-mb pressure levels. Usually for each day two sounding profiles at 0GMT and 12GMT (or 3GMT and 15GMT) were reported. Since the COOP stations have only one reading daily whereas the sounding station has two readings, the twice daily sounding profiles were averaged together to obtain a daily profile of upper air variables.

3 Methodology

In general, majorities of the precipitation in Sierra regions is thought to be the combined effect of two factors; orographic lifting and availability of moisture. Orographic lifting of an air mass is provided by the interaction of synoptic-scale flow with terrain and is relatively deterministic and depends upon the direction of the incoming wind with respect to the orientation of barrier. If the direction of air flow is perpendicular to the orientation of the mountain range, maximum orographic lifting is expected. On the hand, the moisture transport depends on air parcel characteristics (such as temperature, relative humidity, and pressure) and wind speed in the lower troposphere, where the moisture is most concentrated. The moisture transport was expressed in terms of moisture flux, taken as the product of specific humidity with the layer mean velocity. The moisture flux was resolved into parallel and perpendicular directions to the orientation of the mountain and only the latter component was considered in the study. That is:

$$Q_T = \sum_{i=850mb}^{i=300mb} v_i \, q_i \, \cos(\theta - \theta_{mtn})$$

where (Q_T) is the total incoming moisture, q_i is the mixing ratio, v_i is the layer mean wind velocity, and $\theta - \theta_{mtn}$ is the angle between the wind and the orientation of the mountain barrier for each layer. The Sierra Nevada is oriented approximately from South-East to North-West and hence the value of θ_{mtn} was set to 150^0. Thus wind coming from 240^0 becomes roughly perpendicular to the mountain range. The summation was carried out over all mandatory levels between 850- to 300- mb pressure. To discriminate the subseasonal impact, the data were grouped into two subseasons as the averages over November, December, January (NDJ) and February, March, April (FMA).

The analysis is carried from two prospective; individual stations, and north and south of the Sierra. In the first case, to examine the response of individual station to upper air conditions, eight stations were selected from the central Sierra, such that both high and low elevations and both lee and windward sides of the range are considered. These stations are listed in Table 1. In the second case, a systematic analysis has been carried out to determine the variations in upper air characteristics during the largest precipitation events in the northern and southern Sierra. For this sake, the COOP stations were divided into two groups based upon their location. These two groups comprised stations located between $35-37^0$ N and $37-40$ N, respectively. Finally, in order to quantify the dependency of observed precipitation on the moisture transport, regression models were formulated and tested. To better understand how this relationship depends on time scales, the analyses were carried out for different aggregation levels, analyzing in turn, 1, 3, 5, 7, and 30 day totals. A separate model was fitted for each of the 191 COOP station.

Table 1: Name and location of some selected stations used in the study

Station Identification Number	Station Name	Elevation (m)	Mean Annual Precipitation (mm)
sd040897	Blue Canyon	1609	1770
sd042338	Deer Creek	1356	1850
sd043551	Grant Grove	2005	1090
sd044374	Jess Valley	1612	460
sd045679	Mineral	1509	1410
sd047292	Red Bluff	104	570
sd047641	Sagehen Creek	1935	950
sd049105	Twin Lakes	2390	1280

4 Results
4.1 Seasonal Variation of Moisture and Precipitation

The climatological means of the vertical profiles of moisture flux, temperature, wind velocity, and specific humidity for each season at Oakland are shown in figure 1. The seasonal mean daily moisture flux was calculated by averaging over all days of a given season for all years. The vertical profiles of seasonal daily mean values of temperature, wind velocity and specific humidity were also determined following a similar procedure. The winter seasons (NDJ and FMA) are characterized by cold temperatures, high wind speed and generally lower specific humidity. Table 2 summarizes the percentage of total annual moisture flux for each season. NDJ is the wettest season carrying 32% of the annual flux and MJJ is the driest season which contributes 20%. Although, temperature limits the specific humidity for the NDJ and FMA seasons, higher wind speeds make the total moisture flux higher for these seasons. The vertical variation of the moisture profile shows that most of the moisture transport is limited to the lowest levels, that is, below 650-mb. Near the surface, wind speeds limit moisture flux; farther up, humidity limits the flux. Between these two opposing influences, the flux reaches a maximum near 800-mb.

Table 2: Seasonal total of incoming moisture.

| Season	NDJ	FMA	MJJ	ASO
% of annual moisture flux	32	25	20	23

4.2 Precipitation, Wind Direction and Moisture Content

The climatological distribution of moisture transport, represented by incoming moisture flux, as a function of wind direction is shown in figure 2. For both seasons, the wind direction that transports the most moisture lies in the sector 180-270°; that is, southerly to westerly winds. This preferred direction develops because winds from southwest are most likely to be associated with higher winds and moisture-laden storm systems, and may also carry subtropical moisture from the eastern Pacific ocean. Easterly winds are likely to occur in a subsidence region, are probably of continental origin and carry less moisture. The more northerly the wind, the greater is the likelihood that the air is of recent polar origin, and thus cooler and less moist. Among the two winter seasons, the mean moisture flux is greater for NDJ.

Figure 2 also shows the fraction of time the Oakland 700- mb wind is blowing from each direction for the entire season (includes days with and without precipitation) and also just for days with precipitation in the Sierra. For the entire season, the predominant wind is westerly (from the west) to northerly (from the north). In order to examine the variation in wind direction with the increasing precipitation totals, this analysis was repeated for days when there was any amount of precipitation (p>0) and then just for moderate to heavy precipitation (p>25mm). The average precipitation recorded at eight stations (listed in Table 1) was taken as representative for the entire region. The wind climatology for days with precipitation (p>0) is not too unlike that for all days, but is a little more frequently occurring in the 180°-360° sector (i.e., southerly to northerly). For days with
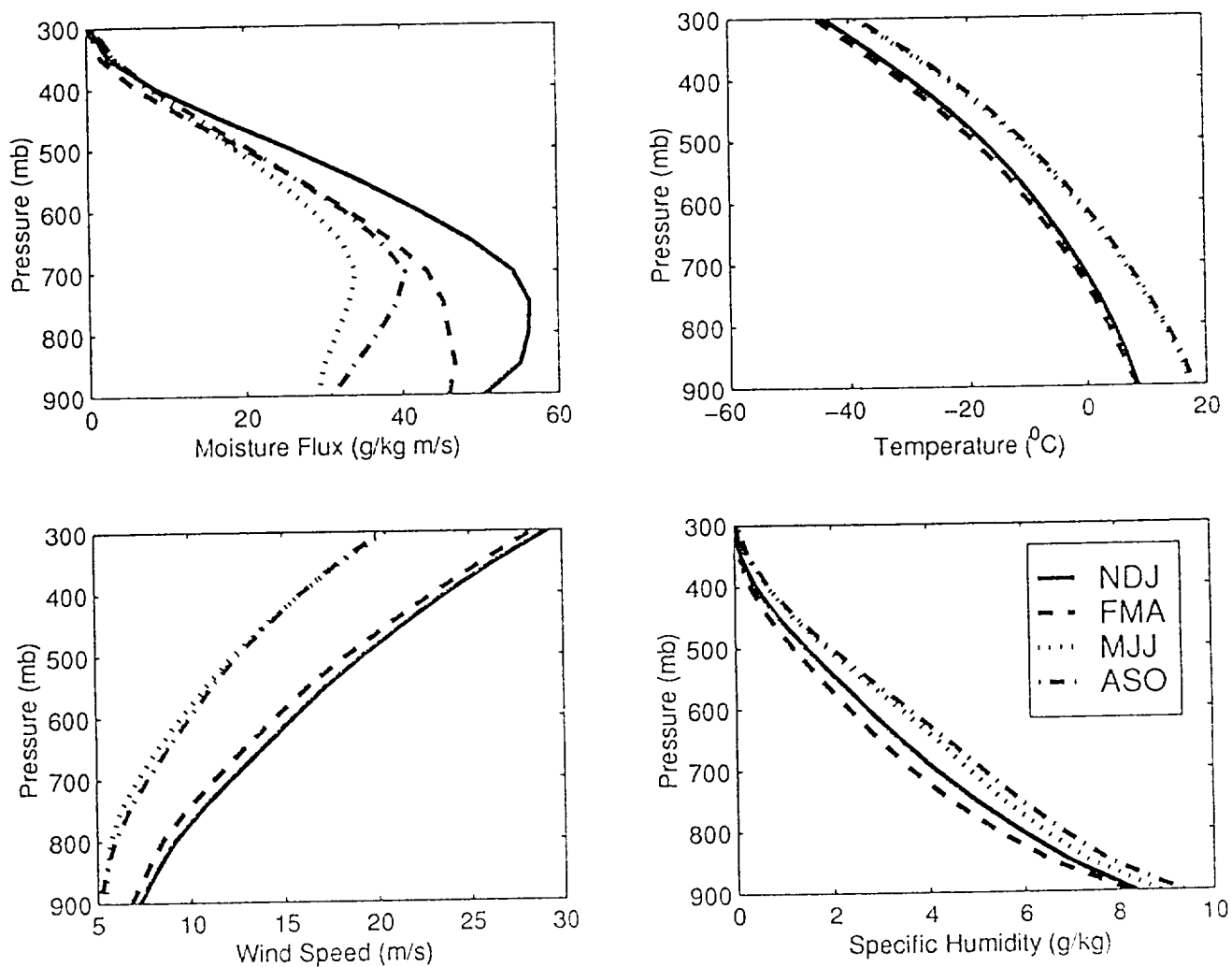
Figure 1 Climatological profiles of moisture flux, temperature, wind speed and specific humidity for November-January (NDJ), February-April (FMA), May-July (MJJ), and August-October (ASO).
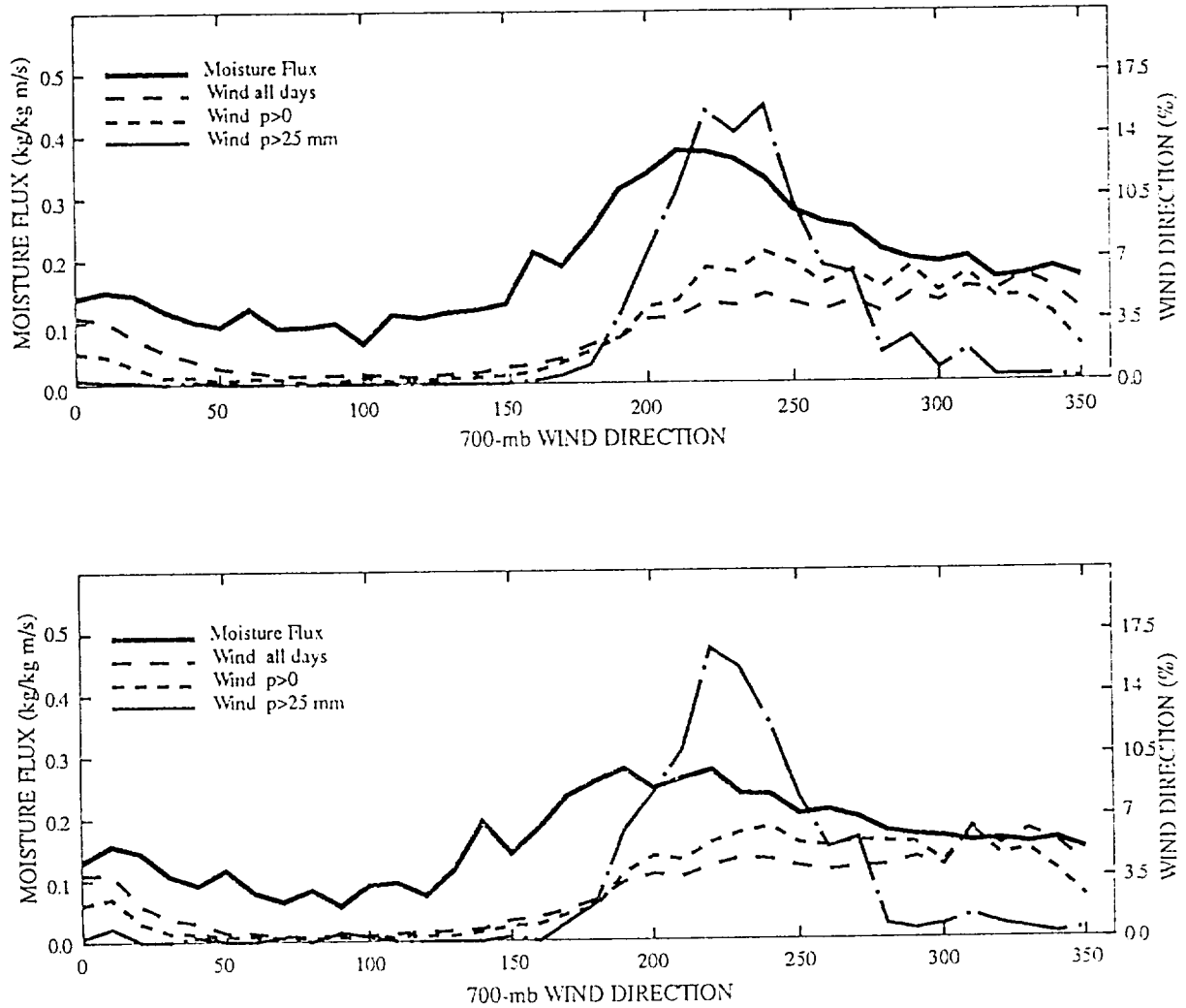
Figure 2 Distribution of climatological means of incoming moisture flux as a function of wind direction and fraction of time the wind is blowing from each direction at Oakland. The incoming moisture fluxes are marked on the left y-axis and is denoted by a solid line. The distributions of winds are marked on the right y-axis and are shown for three cases; (a) for early winter (NDJ), and (b) late winter (FMA).

increasing precipitation, the wind distribution is southwesterly (close to 220-240^0) and both early and late winter display a similar tendency. This peaking of the direction of incoming wind with an increase in precipitation suggests that heavy precipitation in the Sierra during both early and late winter seasons is caused by similar local mechanisms.

Composite vertical profiles of moisture flux, temperature, wind speed and specific humidity above Oakland associated with successively increasing Sierra precipitation amounts are shown in figure 3. As daily precipitation becomes larger, the amount of incoming moisture flux, air temperature, wind velocity and specific humidity are all greater. Also, the wind direction becomes more clustered around the 240^0 direction. This, together with the preferred wind direction for moisture transport, indicates that heavy precipitation in the Sierra is largely combined to days with warm and humid southwesterly winds.

Figures 2 and 3 signify the importance of moisture transport and orographic lifting for enhancing Sierra precipitation amounts. As mentioned earlier, precipitation in mountainous regions is maximized by the optimal combination of moisture transport and orographic lifting. The moisture transport is controlled by synoptic conditions whereas orographic lifting is dictated by interactions between the underlying terrain and the wind fields. Much of the Sierra range is oriented along a line running northwest-to-southwest, so that a wind blowing approximately from 240^0 would produce the greatest orographic effect. Figure 2 shows that, overall there is a difference between the wind direction associated with greatest moisture transport (180-240^0) and the wind direction associated with greatest precipitation (220-240^0). This difference suggests that for heavy precipitation in the Sierra, orographic lifting is important in augmenting incoming moisture and storm dynamics.

4.3 Upper Air Temperature and Precipitation

The frequency of daily precipitation events as a function of the 700-mb temperature over Oakland is presented in figure 4. Distributions are shown for two regions located in the south (between 35-37^0 North) and central Sierra (between 37-40 North) and for three precipitation thresholds, that is, $p > 0$, $p > 12$, and $p > 25mm$. For each case, the threshold precipitation represents the average precipitation over all stations from the respective region. In mountainous region, the temperature of incoming air has two opposing effects in the precipitation amount. First, higher temperature allows higher amount of moisture transport. Second, higher temperature needs higher lifting for condensate to form. Between these opposing factors, the Oakland 700-mb temperature for maximum frequency of precipitation in the Sierra lies close to -2^0 C. For rainy days, that is $p > 0$, the frequency distribution of precipitation for both regions exhibit almost identical patterns. For the northern Sierra, with an increase in the precipitation threshold, that is, $p > 12$ and $p > 25mm$, the Oakland 700- mb temperature still lies close to -2^{0}C range. However, for stations located in the south of the Sierra range, the temperature associated with the maximum frequency of precipitation decreases to close to -7^0 C. This variation in the 700- mb temperature associated with the maximum frequency of precipitation events in the northern and southern Sierra may be associated with the location of cold sector of storms relative to Oakland. It is likely that when the southern Sierra is getting heavy precipitation, the cold sector of a storm system has already penetrated the Oakland
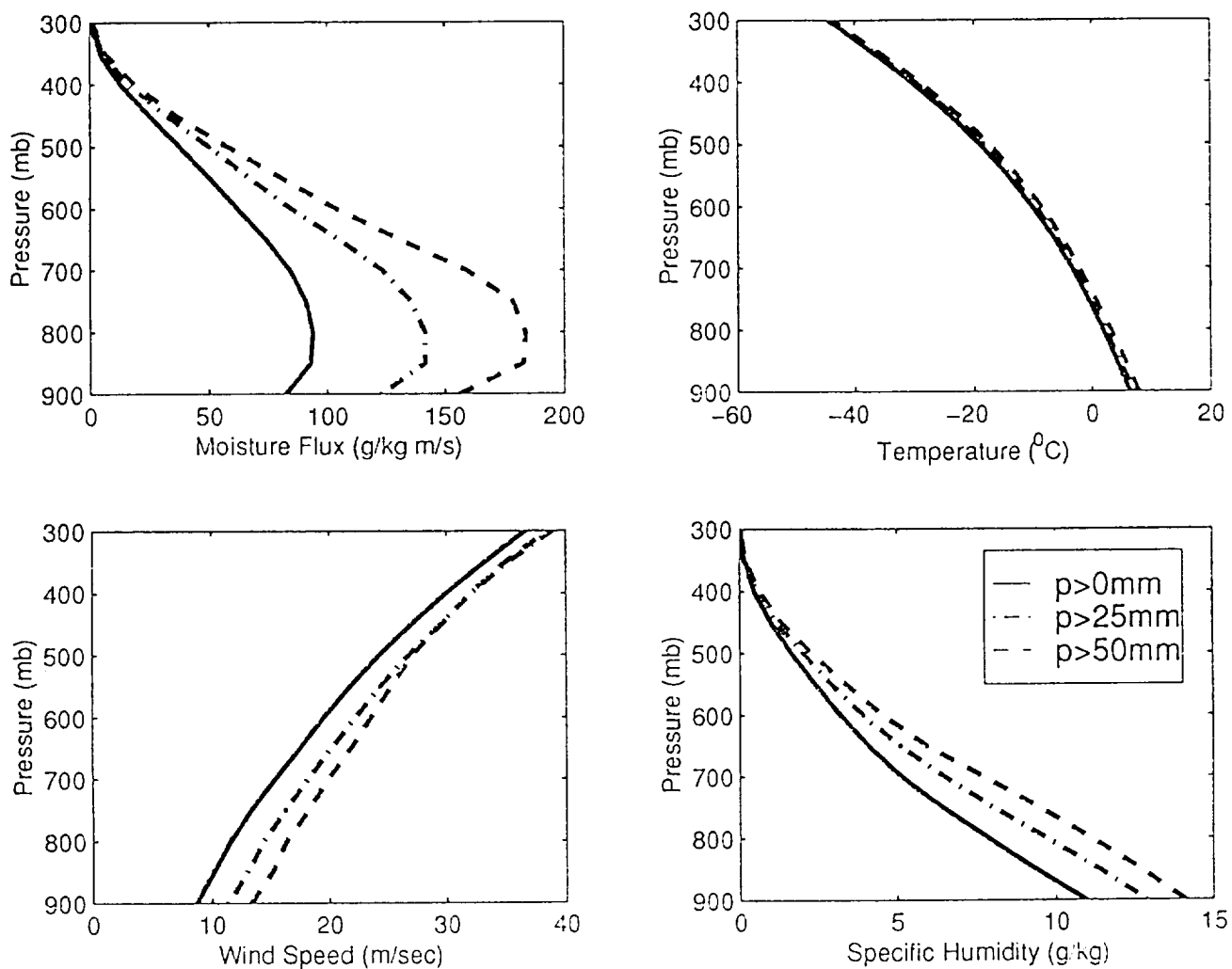
Figure 3 Climatological distributions of the vertical profiles of moisture flux, temperature, wind speed and specific humidity for early winter (NDJ) at Oakland during storm events.
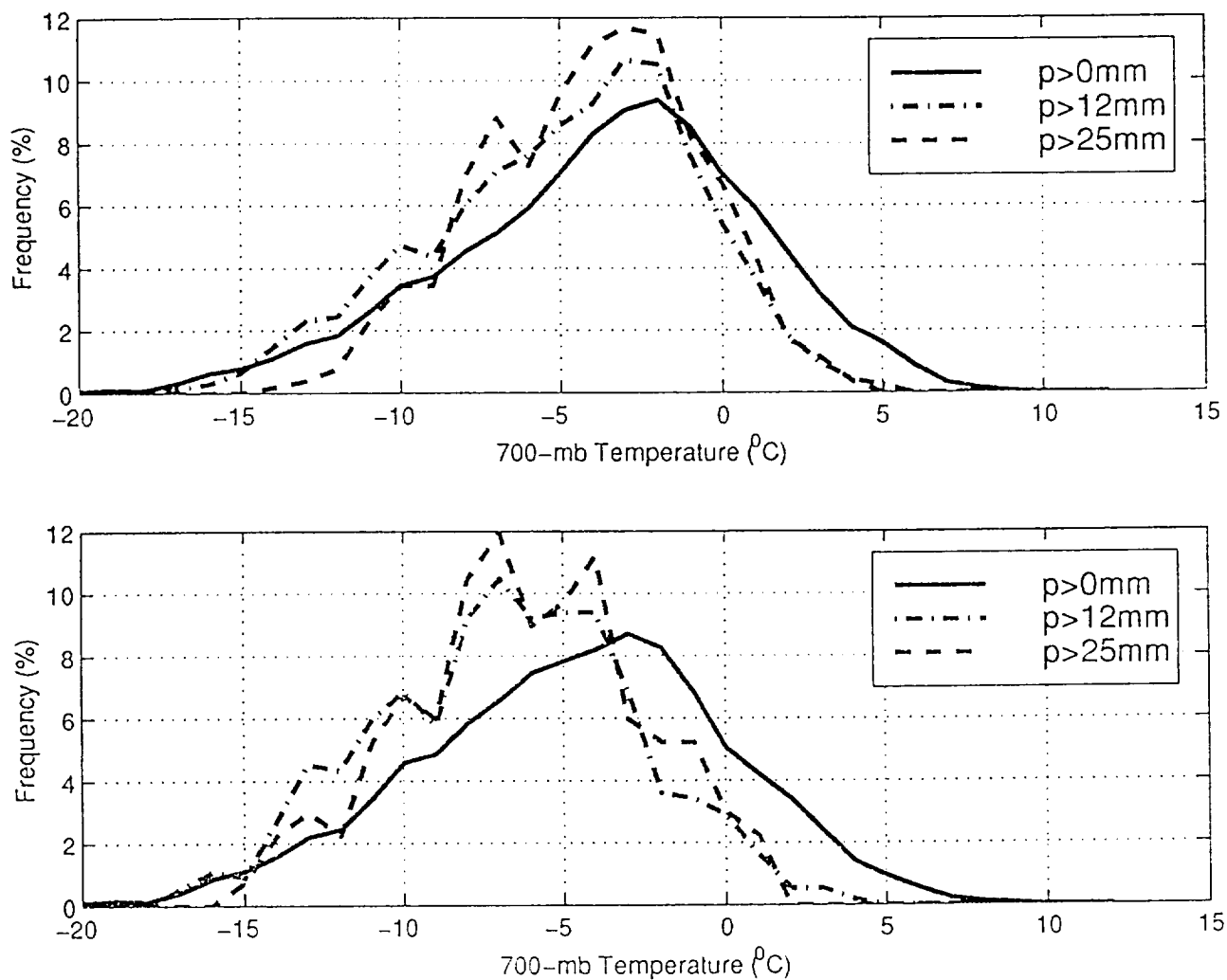
Figure 4 Plots relating 700-mb temperature at Oakland and frequency of precipitation totals for early winter (NDJ) (a) averaged over stations from the northern Sierra (37-40°N) and (b) averaged over stations from the southern Sierra (35-37°N). The distribution are shown for three cases, that is, days with some precipitation (p>0) (solid), days with moderate precipitation (p>12mm) (dashed-dotted line), and days with heavy precipitation (p>25mm) (dashed line).

sounding station. Interestingly, when the 700-mb temperature becomes warmer than $6^{0}C$ there is practically no precipitation in the Sierra. Presumably, at warmer temperatures the orographically forced lifting is not sufficient to bring the air parcels to saturation. Also when air is warm, pressure is higher and hence storm dynamics are not likely to be very intense.

4.4 Prediction of Precipitation Totals Using Incoming Moisture

Linear models were formulated to "predict" the at-site precipitation totals as a function of moisture transport. To account for the orographic effect, only component of the incoming moisture that is nearly perpendicular to the Sierra Nevada range was considered. Successively longer aggregations were considered; particularly 1, 3, 5, 7 and 30 day time periods. Separate models were developed for each station and for each time period. The skill of each model was examined using the coefficient of determination (R^2) value. The average length of sample size and average R^2 values are given in Table 3. The skill of the model is lowest for the daily time scale (average $R^2 \sim 0.22$) and increases with aggregation time scale. After the aggregation scales of 5-7 days, the corresponding incremental increase in the value of R^2 becomes marginal. In terms of incremental increase in the model skill, aggregation time scale between 5-7 days can be considered optimal. Interestingly, storms having durations between 3 and 5 days are most frequent and responsible for moderate to heavy precipitation (10-30 mm/day) in the Sierra region (Cayan and Riddle, 1992). The analysis was repeated by including other variables, namely 700- mb wind speed, temperature and atmospheric stability. However, gain in model skill was marginal. Although not shown here, no systematic variations in the value of R^2 were observed for stations located in the low and high elevations of the mountains.

Table 3:   Aggregation scales, length of sample and R^2 values of the linear model (Precipitation = f(incoming moisture))

Aggregation Time (day)	Early Winter (NDJ)		Late Winter (FMA)	
	Average length of series	R^2	Average length of series	R^2
1	1585	0.22	6283	0.19
3	528	0.40	2050	0.35
5	330	0.48	1219	0.41
7	225	0.50	872	0.44
30	64	0.54	203	0.54

5. Summary and Conclusions

There is more moisture transport within the Sierra in winter than other seasons, mostly because winds are strong during winter. Both frequent and heavy precipitation episodes in the Sierra

are almost always associated with southwesterly winds and they have some preferred temperature range as well. Based upon the historical sounding data at Oakland, the direction of wind for greatest moisture transport has a broad maximum from about 180-270°. On the other hand, the frequency of precipitation is more sharply peaked for southwesterly (220-240°) winds and when the 700- mb temperature is close to -2°C. This favored wind direction and temperature range indicates that orographic lifting is at least as important as the moisture transport in producing precipitation in the Sierra Nevada.

Linear models were formulated to describe the observed precipitation totals as functions of the total moisture transport. To take into account the orographic lifting, component of the moisture flux that is perpendicular to the direction of the Sierra ridge orientation was considered. For daily time scale, the model was able to explain about 22% of variability and model skill increases with an increased in aggregation time. In terms of incremental gains, the model performed best for aggregation periods between 5-7 days. This time scale might be associated with the duration of the most frequent winter storms in the Sierra.

One major application of this study lies in making estimates of heavy precipitation using upper air statistics. The narrow ranges of wind direction and upper air temperature associated with extreme precipitation, provide a predictive tool for upcoming heavy precipitation events using large scale (GCM or NWS) forecasts.

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Related Publications

1. Pandey, G. R., D. R. Cayan and K. P. Georgakakos, "Precipitation structure in the Sierra Nevada of California during winter", JGR, Atmosp. (Submitted, Aug. 1998).

2. Pandey, G. R., K. P. Georgakakos, and D. R. Cayan, "Precipitation modeling in mountainous region: A review", Draft.