LARGE-SCALE AIR-SEA INTERACTION AND ATMOSPHERIC CIRCULATION PATTERNS

By

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Introduction

The Climate Research Group at the Scripps Institution of Oceanography was formed in 1975 as an extension of the North Pacific Study and NORPAX. NORPAX is a multi-university program aimed at improving our knowledge of the mechanisms of large-scale air-sea interaction and the possible stabilizing and deterministic influences of the oceans upon the atmosphere.

We have been engaged in these studies since 1968. During this period we have learned a great deal. However, the interactions within the atmosphere itself and the influences of changing boundary conditions—at the earth's surface and at the top of the atmosphere—seem to be incredibly complex. We do feel that we have at least learned enough to begin asking the right questions.

In this paper I will very briefly skim over the high points of the winter season's atmospheric circulation, large-scale air-sea interaction and seasonal climate forecasting. Then the last three winter's precipitation patterns in the western United States will be linked to the large-scale atmospheric circulation and North Pacific sea surface temperature patterns. Our forecasts based upon sea-surface temperature will also be shown.

Background

The Head of the Climate Research Group, Dr. Jerome Namias, was the founder and for 28 years Chief of the Long-Range Prediction Group of the National Weather Service. During this period he spent a great deal of time examining the possible causative factors for the observed persistence and recurrence of large-scale atmospheric circulation patterns, (Namias, 1975). The atmosphere has a theoretical relaxation time on the order of two weeks. This means that any perturbation in the normal seasonal cycle of the general circulation should decay to an unrecognizable level in two weeks or less. However, a coherence in the upper level steering currents and resultant weather and climate patterns is observed on time scales of weeks, months and even years. Abrupt changes or shifts in the patterns also occur.

This can be illustrated in the percentage of normal precipitation over the western United States for the last four winters (Fig. 1). We see a generally moderate precipitation pattern, but with the beginning of the drought in northern California and Nevada during the winter of 1975-76. This lower than normal rainfall area persisted and expanded over more than a year's period, resulting in the great drought shown in the winter of 1976-77 (Namias, 1978a). This general pattern persisted until into the winter of 1977-78 (Namias, 1978b), when an abrupt shift to much above normal precipitation took place over most of the area. This past winter of 1978-79 was again generally moderate, with the exception of the far Southwest which was under the influence of an influx of tropical air.

The atmosphere is simplistically a gigantic heat engine, driven by incoming solar energy, with the normal seasonal changes being produced by the changing sun angle. There is a net gain of heat in the tropics and temperate latitudes south of 40°N and a net loss of heat in the more northerly latitudes. The majority of the heat transfer from south to north is accomplished by the atmosphere; the oceanic circulation also plays an important role.

Since even severe weather and climate anomalies observed on the seasonal and annual time scales are merely minor perturbations in the overall seasonal cycle, we are forced to examine small changes in the atmosphere and its boundaries in a search for predictive factors. Figure 2 illustrates most of the presently identified factors. Any change in

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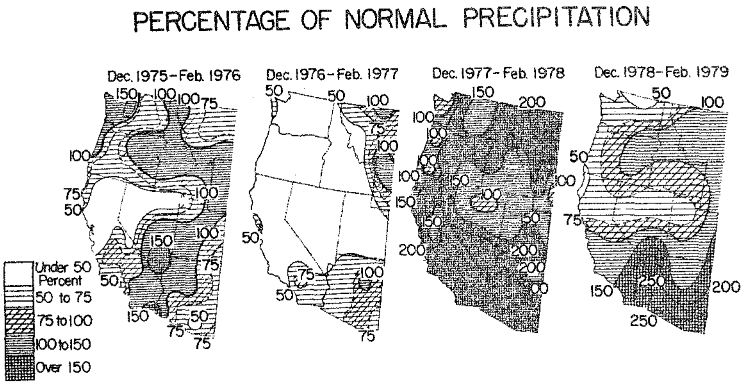


Figure 1. Percentage of normal precipitation observed over the western United States for the last four winters. (From Weather and Crop Bulletin).

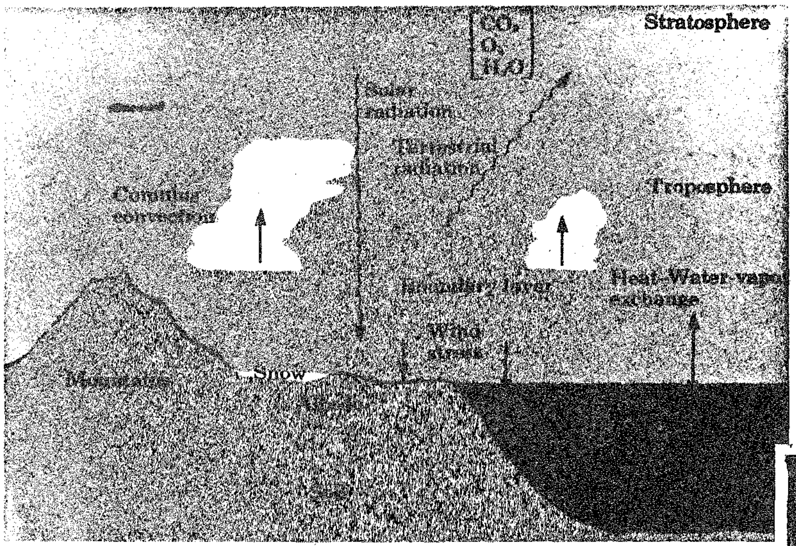
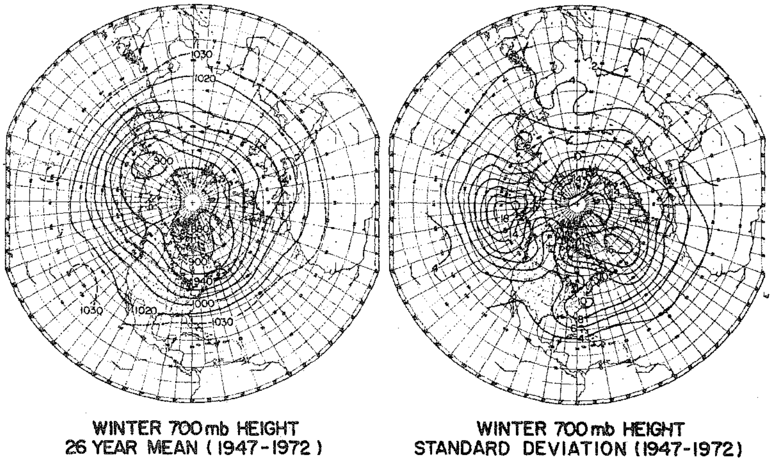


Figure 2. Representational sketch of atmospheric energy exchange parameters.



WINTER 700 mb HEIGHT 26 YEAR MEAN (1947-1972)

WINTER 700 mb HEIGHT STANDARD DEVIATION (1947-1972)

Figure 3. Long period (1947-1972) mean (left) and standard deviation (right) of 700 mb height for the winter season. Contours are labeled in tens of feet.

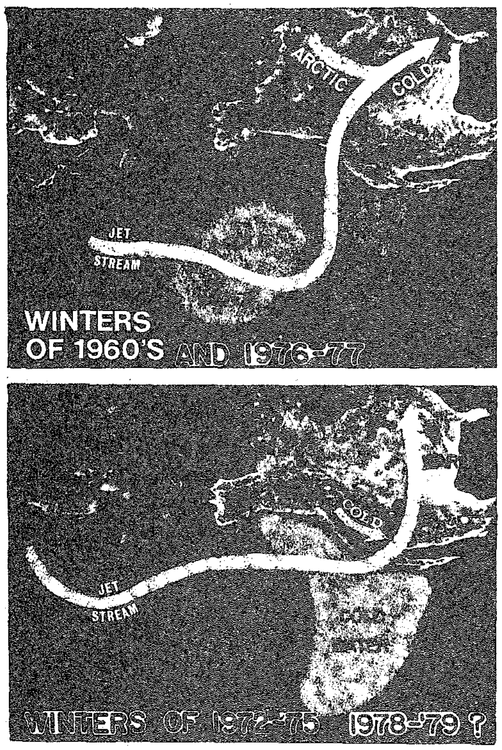


Figure 4. Simplified diagrams of representative Pacific sea-surface temperature anomalies, jet stream paths and resultant U.S. temperature anomalies.

the total incoming solar radiation or its spectral distribution is certainly important, but has not yet been conclusively demonstrated on the seasonal time scale. The primary atmospheric factors involve changes in transmission or reflection of solar energy by changes in carbon dioxide, ozone, particulate matter in the form of smoke and dust, and water in the form of water vapor and clouds. Changes in the rate of poleward heat transmission due to broad changes in atmospheric and oceanic circulation patterns can account for relatively short period lag effects in the atmosphere and much greater lags in oceanic temperature changes. Continental influences are primarily changes in albedo or surface reflectivity due to changes in ice and snow cover and, to a lesser degree, changes in vegetation. Residual soil moisture is also important, primarily during the warm seasons in continental interiors. While mountains are stationary features on our time scales, their presence can magnify the effects of subtle shifts in atmospheric flow patterns.

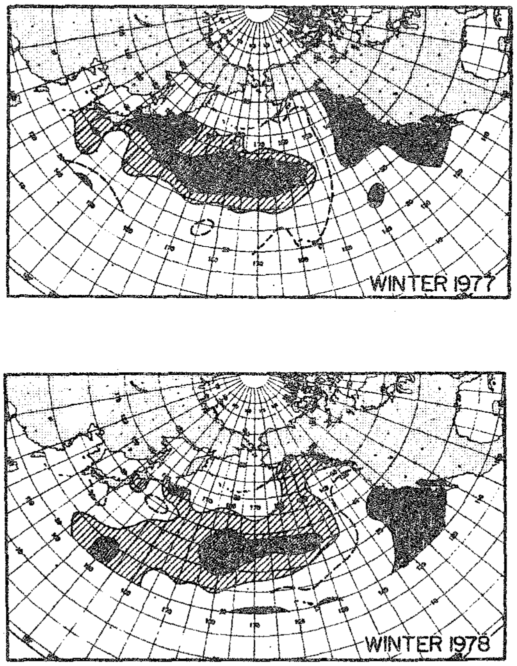
Finally, we turn to oceanic-atmospheric interactions, the primary research objective of the Climate Research Group. The heat capacity and viscosity of the ocean is about 1000 times greater than the atmosphere. As much heat energy is contained in the upper 10 meters of the oceans as in the entire atmosphere. We see thermal changes in the ocean extending down as deep as 300 meters, indicating the ability of the surface layers of the ocean to act as a source or sink for large changes in heat energy. The relatively sluggish movement of the oceans provide a much greater theoretical persistence in temperature anomalies. There is a tremendous amount of moisture and heat energy extracted from the oceans by the atmosphere in the temperate latitudes.

Returning to the atmosphere and examining the long term mean mid-tropospheric steering currents (Fig. 3, left), we can perhaps visualize our winter storms emanating from Siberia as very cold, dry cyclonic centers, then being steered across the North Pacific extracting vast amounts of heat and water vapor from the underlying ocean before coming ashore in the Oregon/Washington area and dropping down into the eastern U.S.. The integrated effects of relatively small differences from the mean sea-surface temperatures or anomalies over large areas could certainly have an effect on the intensity and moisture content of the winter storms and their associated fronts. These large Pacific cyclones tend to follow a path maximizing their energy uptake (i.e. warmer water) as do their smaller counterparts, hurricanes and tornadoes. An additional energy source, increased baroclinicity, is derived from temperature gradients, particularly the case of warmer temperatures to the right of their course and colder to the left (in the Northern Hemisphere).

Any change in the mid-tropospheric steering currents and the resultant storm tracks is of even more critical importance in determining changes in weather and climate. At the risk of confusing the reader still more, it must be pointed out that the 700 mb height contours shown in Figure 3 are the average of 12 hourly weather maps and contain the integrated effects of the storm movements. The standard deviation or variability among winters of the steering currents is shown on the righthand side of Figure 3. We can see that the major variability occurs over the eastern North Pacific, in the area dominated by the Aleutian Low. A secondary area of variability occurs over the North Atlantic. We have chosen to study air/sea interaction over the Pacific because it is upstream from the United States and may have the greatest effect on the atmosphere.

If we turn attention back to the lefthand side of Figure 3, we see that the hemispheric circulation pattern appears to be in the form of a 3-lobed wave. These waves are referred to as the planetary waves or Rossby Waves. The area of closest contour spacing (highest speed) marks the position of the lower portion of the jet stream, which is often used to trace the high speed core of the planetary circulation. While there can be from one to six or seven waves around the globe, the dominant wavenumbers are 3, 4 and 5.

Two different jet stream paths and compatible sea surface temperature anomaly configurations are shown diagramatically in Figure 5. In both cases the jet stream dips to the south over the colder than normal water and ridges over the warmer water. In the upper path, the cold left—warm right effect is apparent, while the opposite case has little effect as indicated in the lower path. In both cases cold, relatively dry air is drawn southward along the descending limb of the planetary wave trough and warm, moist air is drawn northward along the ascending limb of the ridge. Also, one can see that a positive feedback relationship between the atmosphere and ocean tends to self-perpetuate and stabilize the planetary wave position, amplitude and wavenumber. This positive feedback appears to be the norm; however, some striking cases have occurred where the ocean



SST$_{DM}$ (ANALYZED TO 1°F)

Figure 5. Sea-surface temperature departures from a 20-year (1947-66) mean for the North Pacific. Analyzed to 1°F.

Principal Tracks of Centers of Cyclones at Sea Level, North Pacific

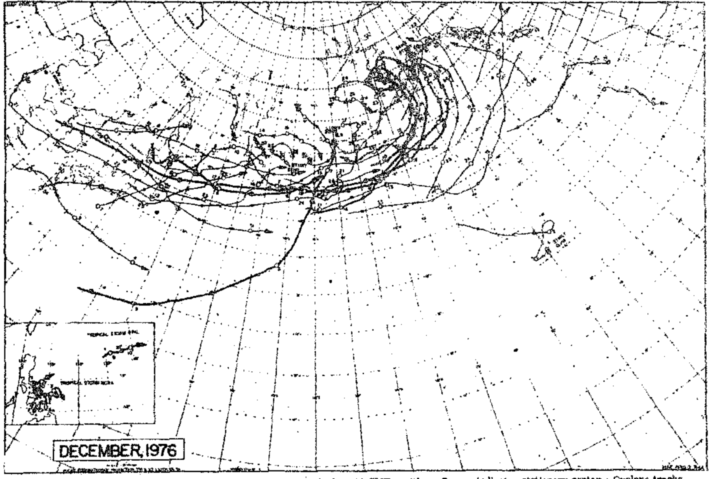


Figure 60.--Open circle indicates 1200 GMT position and closed circle 0000 GMT position. Square indicates stationary center. Cyclone tracks marked with a heavy line are described in the Smooth Log.

Figure 6. Principal tracks of centers of cyclones at sea level, North Pacific for December, 1976. (From Mariners Weather Log).

Principal Tracks of Centers of Cyclones at Sea Level, North Pacific

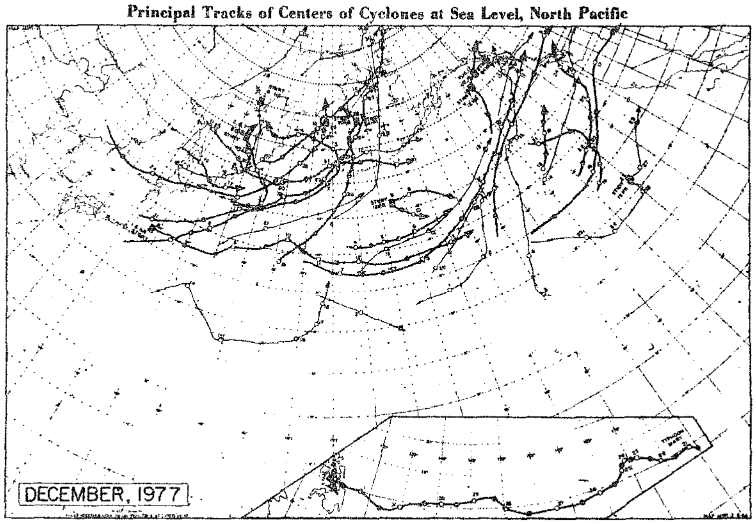
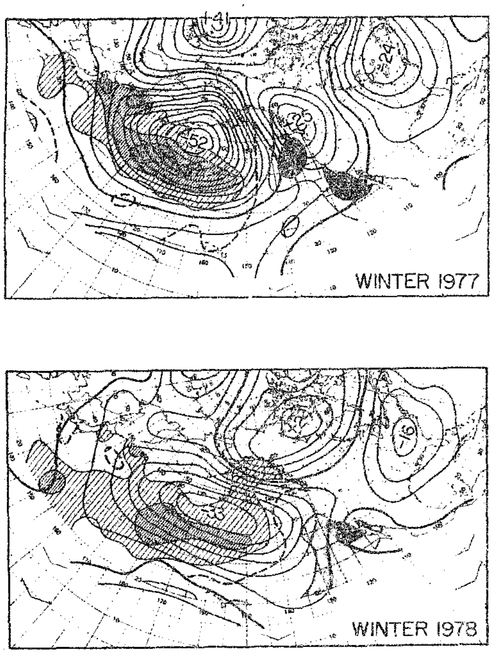


Figure 53.--Open circle indicates 1200 GMT position and closed circle 0000 GMT position. Square indicates stationary center. Cyclone tracks marked with a heavy line are described in the Smooth Log.

Figure 7. Principal tracks of centers of cyclones at sea level, North Pacific for December, 1977. (From Mariners Weather Log).



700 mb HT$_{DM}$ ANALYZED TO 50ft.)
SST$_{DM}$ (ANALYZED TO 1°F)

Figure 8. Sea-surface temperature departures (F) as in Figure 5 and 700 mb height departures (tens of feet) for the North Pacific.

and atmosphere appeared to be acting independently or in a negative feedback sense for relatively short periods of time during climatic breaks or transitions.

The main point of this background discussion has been to indicate that determining the position, amplitude and wavenumber of the winter mean planetary wave circulation is the first key step to the derivation of a successful winter climate forecast. Furthermore, one possible method of estimating the planetary wave configuration would be to predict the sea-surface temperature anomaly pattern for the winter and derive the compatible atmospheric flow pattern, assuming a positive feedback exists.

The Last Three Winters

During the winters of 1976-77 and 1977-78 the sea-surface temperature anomaly patterns in the North Pacific were, at first glance, quite similar (Figure 5), with cooler than normal water over most of the area and warmer than normal water along the Pacific Coast. Looking a little closer, we can see that in 1977 the dashed zero anomaly line was oriented almost north-south, while in 1978 it was much more east-west. In both cases we observe the warm to the right and cold to the left of the normal storm path that was mentioned earlier.

Comparing the observed storm tracks for December, 1976 (Fig. 6) and December, 1977 (Fig. 7) a striking difference is apparent. In December, 1976 and the remainder of the winter of 1977 the cyclones held a rather tight path across the Pacific and turned abruptly to the north into Alaska rather than continuing on their normal course into the western U.S.. In fact, three or four actually turned back on themselves. The great western drought of 1977 is quite obvious here, with only one minor storm skirting the Northern California coast. It would appear that the storms were following the strong north-south sea-surface temperature gradient.

The storm tracks for December, 1977 (Fig. 7) were quite different. There were two preferred paths. One set of storms seemed to get lost in the warmer water west of the Aleutians. The dominant storm track for the winter of 1978 led the storms into the Northwest in December and then farther down the coast as the winter progressed. In this case the oceanic temperature gradient served to enhance the normal storm track. The warmer waters off the Southern California coast provided an extra source of moisture.

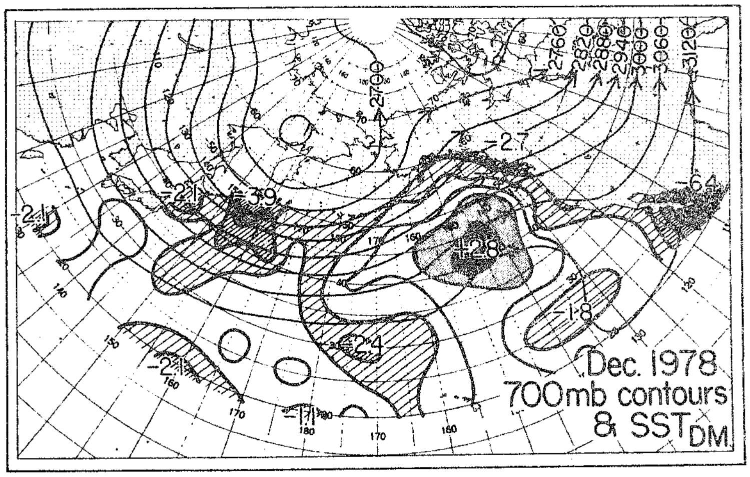
Superimposing the observed 700 mb height anomalies on the sea-surface temperature charts for the winters of 1977 and 1978 (Fig. 8) makes the drought of 1977 and the heavy precipitation of 1978 quite obvious. Both maps have a low centered over the colder than normal waters. In 1977 a blocking high pressure cell dominated the Pacific Northwest and extended its influence throughout the West. Notice that if any storms had broken loose onto a more southerly course as they often do near the end of the winter season, they would have come in to Southern California and Arizona. In the winter of 1978 the storms were unimpeded and, in fact, gained moisture from the indicated anomalous southerly flow all along the Pacific Coast.

We have not yet worked up a comparable set of charts for this last winter, but we do have the December, 1978 sea-surface temperature anomalies and the actual steering currents (not anomalies). The oceanic temperature anomaly pattern does not indicate any striking features, with the exception of the above-normal area south of the Gulf of Alaska. Here we see some evidence of troughing of the planetary circulation over the lower than normal temperatures and a definite ridging over the warmer than normal area. This pattern would lead to a rather normal winter with the storm tracks depressed somewhat to the south.

Forecasts

The procedure that we have been using in our seasonal forecasting experiments is outlined in Figure 10. This flow chart is sufficiently detailed for the purposes of this discussion and will not be elaborated upon here. Our forecast for the winter 1976-77 North Pacific 700 mb height anomaly is shown in Figure 11. Referring back to the actual observed pattern in Figure 8, one can see that the essence of the pattern is captured, but the detail is poor or misleading. The "19" high center is physically unrealistic and was disregarded when the forecast was made. The western drought is, however, the only precipitation forecast consistent with this pattern.

Figure 9. Sea-surface temperature departures from a 20-year mean (1947-66) contoured in 1°F and 700 mb height contoured in meters for the North Pacific for December, 1978.



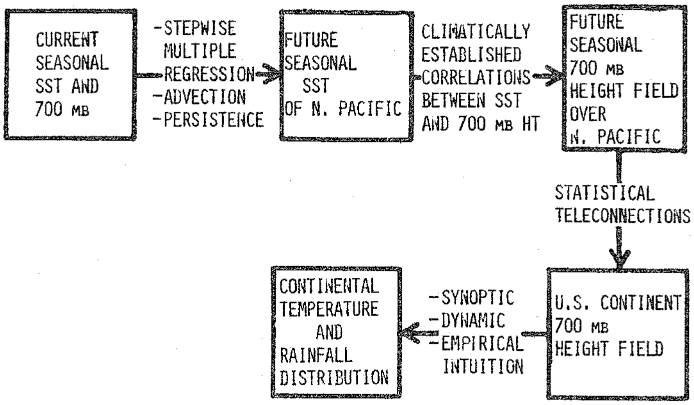
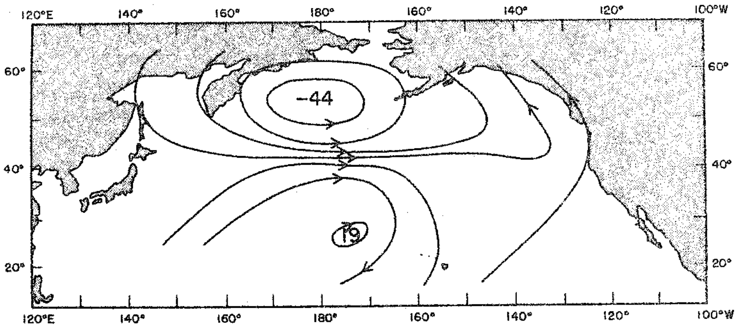


Figure 10. Flow chart of steps in preparing the seasonal predictions shown in Figure 12.

Figure 11. 700 mb height departures from a 26-year mean (1947-72) for winter 1976-77 specified from November, 1976 sea-surface temperatures assuming advection by the mean surface currents.



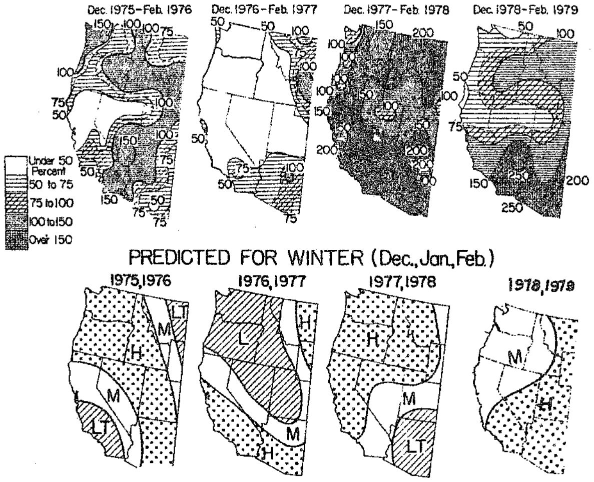


Figure 12. Percentage of normal precipitation (as in Figure 1) observed (top) and predicted (bottom) for 3 equally probable classes of heavier than normal (H), moderate (M) and lighter than normal (L or LT).

The last figure (Fig. 12) compares the observed and forecast precipitation for the past four winters. Our forecasts, derived using the principals outlined above, are divided into three equally probable classes or terciles. Since precipitation does not follow a Gaussian distribution, it is difficult to relate percentages and terciles. A little study will reveal that the gross features of precipitation were fairly well represented, but that individual watershed areas could be poorly predicted. To our knowledge the forecasts shown here are indicative of the state of the art in seasonal precipitation forecasting. We have one specific research project aimed at improved precipitation forecasting in the western U.S. which may lead to a moderate improvement in skill of our tercile forecasts. The attainment of quantitative forecasts for individual catchment basins is still a long way off.

Acknowledgments

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