Evaluation of Ceiling and Visibility Prediction: Preliminary Results over the California Coast using COAMPS

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OBJECTIVE

Introduction

Accurate forecasts of ceiling height and visibility are critical to ensuring the safe operations of Naval aircraft. When operating in regions of low ceilings, aircraft carrier commanding officers position their ships in "holes" for takeoffs and landings. In response to a need for accurate weather representation within the battlespace environment, the Naval Research Laboratory (NRL) in cooperation with the National Center for Atmospheric Research (NCAR) is developing a real-time weather prediction system called NOWCAST. NOWCAST is designed to improve weather prediction in the 0-6 hour time range by integrating shipboard observations, satellite and radar data, and numerical weather prediction (NWP) model forecasts into one product. An initial requirement of the NOWCAST project is a ceiling and visibility product.

A few studies have attempted to evaluate algorithms to predict ceiling and visibility (C&V). A recent study by Stoelinga and Warner (1999; hereby referred to as SW1999) attempted to predict C&V using forecasts from the Pennsylvania State University – NCAR 5th Generation Mesoscale Model (MM5) as input into two C&V prediction algorithms. Each algorithm is referred to as a Translation Algorithm (TA) since the algorithm translates the output of a numerical model into another useful weather parameter. SW1999 examined the performance of the C&V TAs during a two-day frontal passage over the northeastern United States in March 1992. While SW1999 found visibility to be reasonably well represented by the TA, the ceiling forecasts showed a tendency to over-predict high ceilings when compared with Surface Airway Observations (SAO) at selected stations in the forecast grid. A qualitative analysis that compared the areal coverage of low ceiling and visibility forecasts with SAOs and operational terminal forecasts yielded similar conclusions.

The motivation of the present study is to further evaluate the TA algorithms described by SW1999 using the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). Notable differences between SW1999 and the present study include the numerical model (MM5 versus COAMPS), the duration of study (2 days versus 6 months), and the location of the forecast grids (northeastern United States versus the west coast of the United States). The results of this study will determine the TA's role in NOWCAST.

Ceiling and Visibility Algorithms

The C&V algorithms used in the present study have been thoroughly described by SW1999, and only a brief description of the algorithms will be given here. SW1999 define the range of visibility as the distance at which light from an illuminated object has been extinguished to 2% of its original value. The following relationship is used to predict the range of visibility, x_{vis},

$$x_{vis} = -\ln(0.02)/\beta \qquad (1)$$

where β is the extinction coefficient. Ceiling height is determined by integrating β vertically over a single grid point until a beam of light shown at the model surface is extinguished to 0.02 of its original intensity.

The extinction coefficient defined by SW1999 includes effects due to cloud water (β_{cw}), cloud ice (β_{ci}), snow (β_{sn}), and rain water (β_{rn}) where,

$$\beta = \beta_{cw} + \beta_{ci} + \beta_{sn} + \beta_{rn} \qquad (2)$$

and,

$$\beta_{cw} = 144.7\ C^{0.88} \text{ (Kunkel 1984) – Cloud Water}$$

$$\beta_{ci} = 2.24\ C^{0.75} \text{ (Rutledge and Hobbs 1983) – Cloud Ice}$$

$$\beta_{sn} = 327.8\ C^{1.00} \text{ (Stallabrass 1985) - Snow}$$

$$\beta_{rn} = 10.4\ C^{0.78} \text{ (Marshall-Palmer) - Rain}$$

$$C \equiv \text{Mass Concentration } (gm^{-3}).$$

A flaw in the calculation of β, acknowledged by SW1999, is the exclusion of any physics to quantify the effects of blowing dust, blowing snow, and aerosols. Modeling of aerosols is particularly difficult given the inadequate observational data required to initialize this field in an NWP model. The effects of the aerosols will be discussed later.

Model Description

COAMPS is a multi-scale, nonhydrostatic model used in an operational and research capacity. A complete description of the physics and dynamics used in COAMPS is given by Hodur (1997). COAMPS initial fields are interpolated from the 1-degree global grids of the Navy Operational Global Atmospheric Prediction System (NOGAPS) for cases where no previous COAMPS forecast fields are available. This condition is referred to as a cold start. When the output of a previous COAMPS forecast is available at the analysis time, the COAMPS fields are used in place of NOGAPS. This condition is referred to as a warm start. The lateral boundary conditions to the model are always provided by NOGAPS. In addition to NOGAPS, observational data is assimilated into the initial model fields using a multivariate optimum interpolation analysis.

The σ vertical coordinate system used in COAMPS normalizes the height of each vertical level in the model relative to the depth of the atmosphere and the terrain surface. Over flat terrain, a sigma level of 10 meters is 10 meters Above Ground Level (AGL); however, over terrain with elevations greater than zero, the height of a 10 m sigma level is less than 10 meters AGL. In the present simulations, the lowest sigma level is chosen to be 10 meters and the depth of the atmosphere is chosen to be 31050 meters.

COAMPS explicitly predicts the values of rain water, cloud liquid water, cloud ice, and snow at each time step. The visibility calculation uses the instantaneous value of each field at the lowest sigma level to calculate the extinction coefficients in Eq. 2. The ceiling height is determined by integrating the value of beta upward over a single grid point until the threshold of 0.02 has been exceeded. The ceiling height is then linearly interpolated to the level where $\beta = 0.02$. Since the explicit moist physics (Rutledge and Hobbs, 1992) are used only in grids with spacing less than 10 km (Hodur 1996), only the forecasts of the finest mesh (9 km) will be considered in this study. Visibility and ceiling height are considered unlimited at ranges greater than 16.1 km and 9 km respectively.

Simulation Description

Each 12-hour forecast during the six-month study is run on a triply nested Lambert Conic Conformal grid positioned over the west coast of California. Fig. 1 indicates the location, resolution, and number of grid points used in each grid.

The California coast has been chosen for several reasons:

- The typical summer weather pattern includes numerous low stratus events for comparison with forecasts.

- A typical fall weather pattern has frequent frontal passages.

- METARs that include observations of ceiling and visibility are available hourly.

- Visible satellite imagery over California is available at a high resolution (1 km).

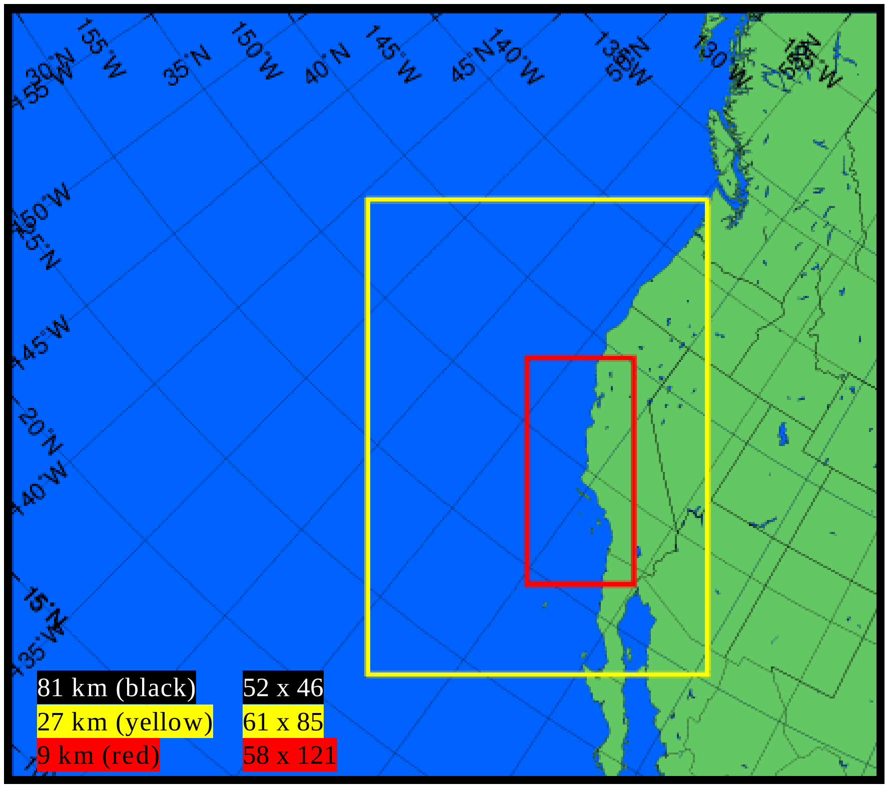


Figure 1. Forecast Grids
The grid spacing and number of grid points are
indicated within the image.

The period of study consists of successive 12 hour forecasts initialized twice daily (00Z and 12Z) beginning 1 July 1999 and ending 31 December 1999. A cold start is used only when the previous 12-hour COAMPS forecast fields are unavailable. Cold starts are indicated in Fig. 2 as the dates following a simulation that was unable to complete (red) or a non-run (white). Several factors contributed to the numerous cold starts in August and September including a disk failure, an unusual lightning strike, and changes to the execution environment. The version of COAMPS was upgraded in October; however, a problem with the code forced the model to be run without a moisture analysis during the entire month. The simulations from October are not included in this study. The moisture analysis was corrected by 1 November, and the model ran without interruption until the end of the year.

For the first month of the study, the ceiling height fields were examined qualitatively through comparisons with visible satellite imagery. Beginning on 16 August, the ceiling (m), visibility (m), temperature (K), and dew point (K) were extracted at selected grid points within the finest mesh and compared with METAR stations. The station locations relative to the grid are shown in Fig. 3. Hourly METAR observations include temperature (°F), dew point (°F), wind direction (degrees), wind speed (knots), ceiling height (feet), and visibility (miles). The METAR observations are converted to units that are consistent with the model forecast fields. Individual grid point values from the model are archived at 3 hourly intervals, and the entire forecast grids of ceiling and visibility are archived at a 6 hourly interval.

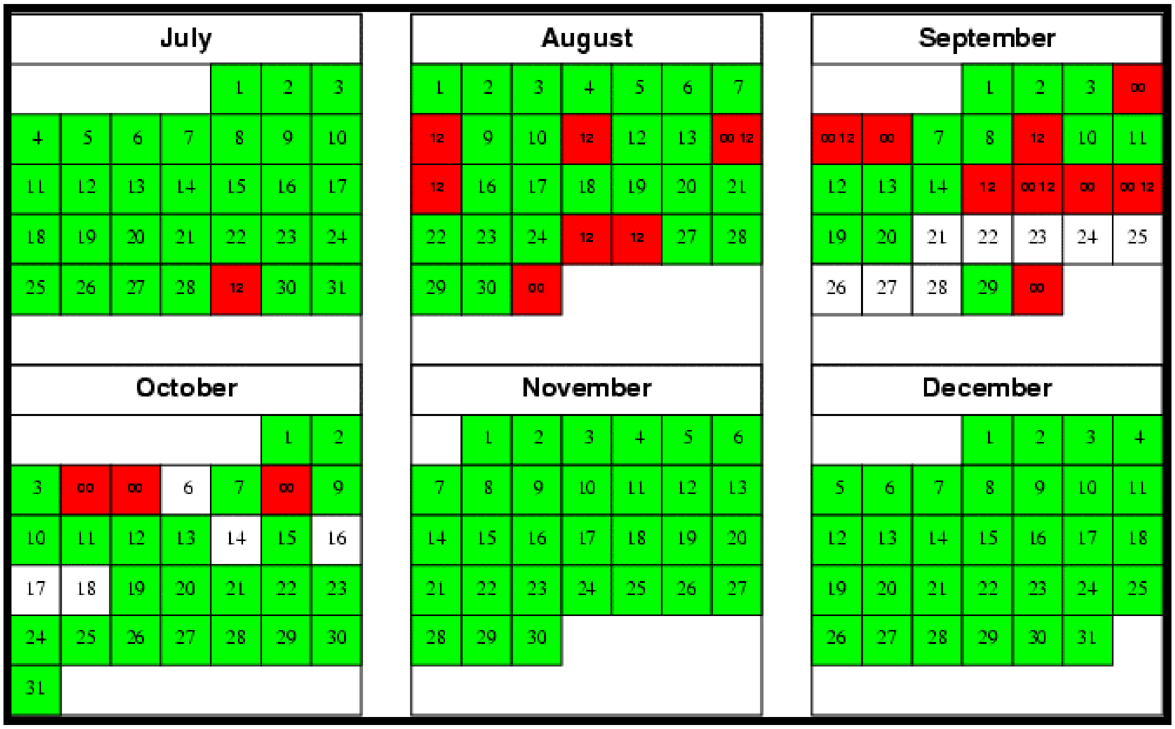


Figure 2. Model Status

The calendar indicates the status of each COAMPS forecast beginning 1 July 1999 and ending 31 December 1999. Green boxes indicate days where two 12-hour forecasts (00Z and 12Z) completed successfully. Red days indicate incomplete forecasts with the analysis time of the forecast indicated on the date. White days indicate no COAMPS forecasts.

RESEARCH ACCOMPLISHED

Validation Against Satellite Imagery

Various synoptic situations are chosen to demonstrate the skill of the algorithms at predicting ceiling height against visible satellite imagery. The comparisons are limited to 18Z (10 PST) and 00Z (16 PST) due to the availability of sunlight. Visible rather than infrared satellite imagery is chosen for the comparisons to be able to view clouds near the Earth's surface; however, in some cases, infrared imagery will be referenced to distinguish high clouds from low clouds within a visible satellite image. Although satellite imagery does not provide a definitive ceiling height to compare against the model, an approximate ceiling height (low, medium, high) can be inferred from cloud patterns and the synoptic/mesoscale conditions. In addition, satellite imagery provides a means to verify the areal extent of a forecast cloud field.

Location (METAR)	Lat.	Long.	Elev. (m)
Bakersfield (KBFL)	35.42 (35.43)	-119.08 (-119.05)	274 (150)
Los Angeles (KLAX)	33.95 (33.93)	-118.44 (-118.40)	0 (32)
Monterey (KMRY)	36.60 (36.58)	-121.82 (-121.85)	168 (77)
San Luis Obispo (KSBP)	35.21 (35.23)	-120.67 (-120.63)	120 (64)
San Francisco (KSFO)	37.62 (37.61)	-122.40 (-122.38)	52 (5)

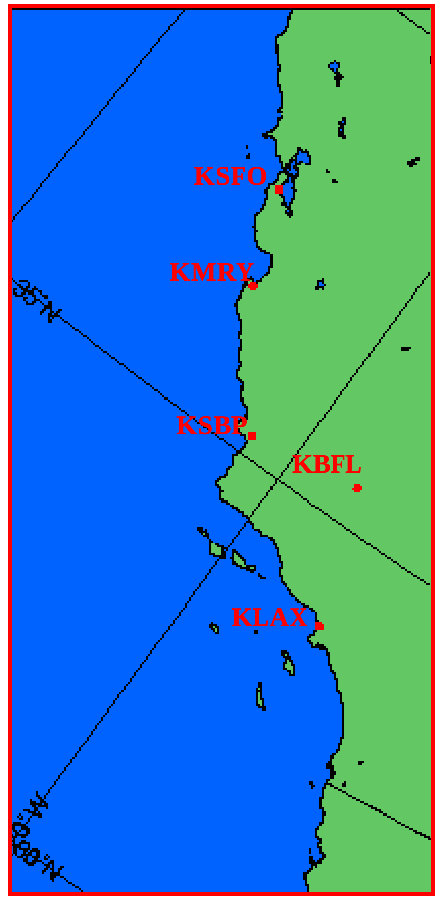


Figure 3. METAR station locations
Latitude, longitude, and elevation of each station in the model are shown in the table above. Parentheses denote the values at the corresponding METAR station.

In the cases described below, the model calculation of ceiling height has been regridded to a region matching the 1 km satellite imagery as closely as possible. A yellow line representing the 200 m elevation height is shown in both images, and the two straight red lines shown in the model images represent the bounds of the forecast grid. Fictitious gradients in ceiling height may be found near the grid boundaries and should be ignored. Ceiling heights are unlimited unless otherwise indicated. Each forecast described below includes a discussion of the timing of the cloud cover, the shape of the cloud patterns, and the approximate height correspondence between the satellite image and forecasted field.

Low Stratus

Fig. 4a shows a cloud pattern typical of the California coast in June and July. In this case, a region of low stratus has progressed up the coast during the 12 hours prior to the valid time of the forecast. The model has correctly predicted the timing of the cloudiness, and the ceiling height forecast matches the coverage and shape of the clouds shown in the satellite image. The ceiling height in the model increases westward in a region where the clouds also appear to thin in the satellite image.

Fronts

Several frontal passages occurred during the month of November. Fig. 4b shows a frontal passage at 18Z on 19 November 1999. The brightest cloud tops in the northwest quadrant of the satellite image indicate the most convective clouds. A thinner high to mid-level cloud precedes the convective band to the south and east. The ceiling height field forecasted by the TA has a shape similar to the clouds shown in the satellite image. The ceiling heights also appear to be correlated with the variable cloud types shown in the satellite image. The lowest ceilings and most convective clouds are found to the northwest, and the highest ceilings and broken clouds are found to the southeast of the convective clouds.

Cirrus

A couple of problems with predicting cirrus on a 9 km grid include: (1) the clouds can be very small scale and unresolveable and (2) these clouds may be thin or nearly transparent. The satellite image in Fig. 4c shows a band of high clouds that has moved north from the ITCZ during the preceding 48 hours. A few mid-level clouds are also present as a result of weak convergence ahead of a trough to the northwest. Infrared satellite imagery (not shown) indicates that the cloud tops are high. Despite the small scales of the clouds, the model appears to have predicted a ceiling height and cloud orientation that is consistent with the satellite imagery; however, a few cloud streaks were not resolved to the north, particularly near KMRY.

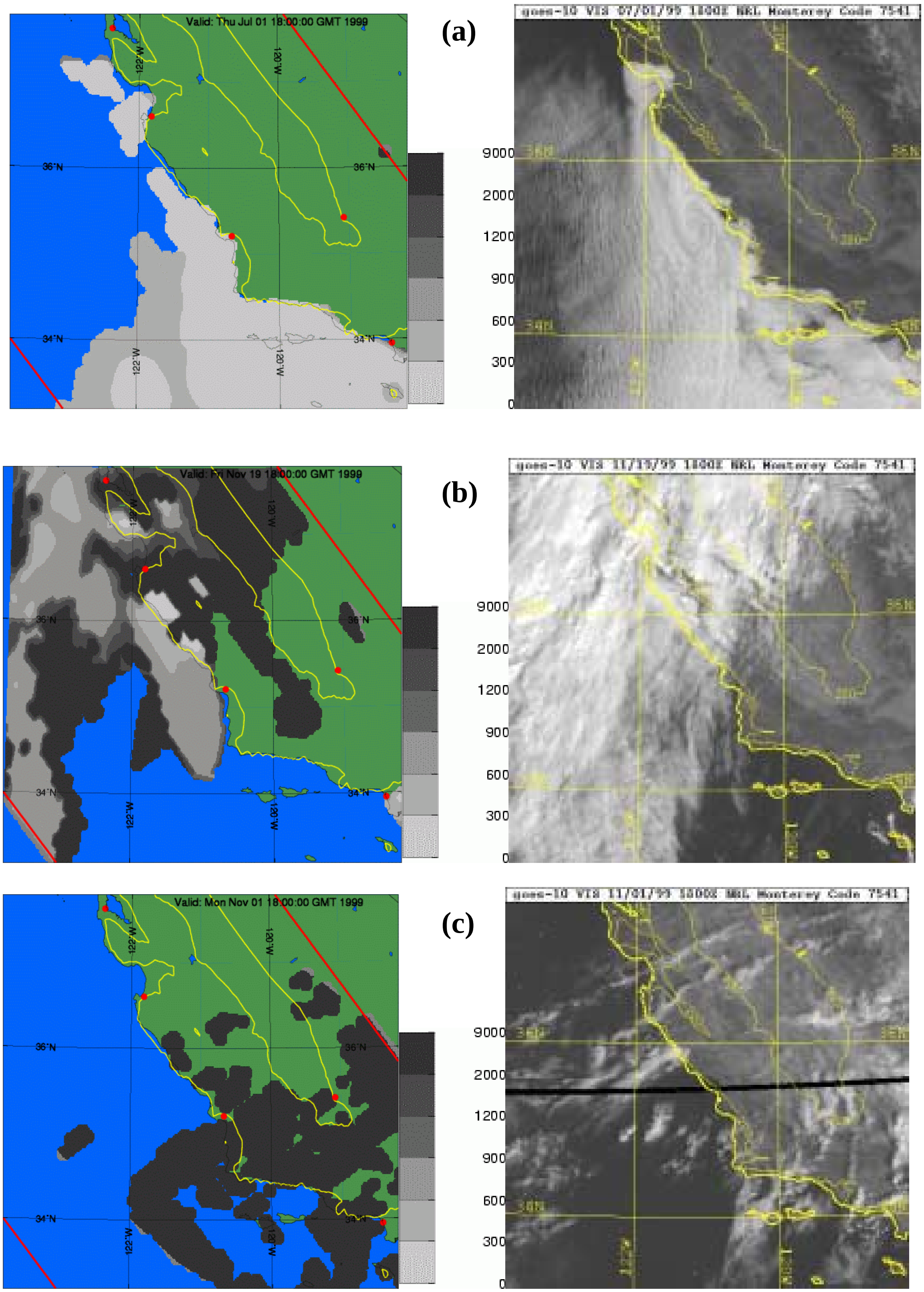
Fog

The model forecast of ceiling height in Fig. 4d indicates a large fog bank in the central valley of California, a feature that is absent in the satellite image. Cases of low cloud over-prediction similar to the event shown in Fig. 4d occurred frequently in the central valley. An analysis of the satellite images prior to the forecast time may be useful to determine whether the model has a problem evaporating low clouds during the morning hours (18Z or 10 PST). Radiation fogs will need to be examined more closely in future studies.

Validation Against METARs

Two time periods from the 6-month simulation are chosen for a quantitative comparison with the METARs: Period 1 - 16 August to 15 September and Period 2 - 1 November to 30 November.

Each period was chosen to minimize the number of cold starts, and maximize the number of forecasted events. The weather in Period 1 is characterized by periods (2-3 days) of coastal stratus followed by periods of clear skies. Period 2 has numerous cold front passages.



(a)
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(b)
Valid: Fri Nov 19 18:00:00 GMT 1999
goes-10 VIS 11/19/99 1800Z NRL Monterey Code 7541
(c)
Valid: Mon Nov 01 18:00:00 GMT 1999
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120°W

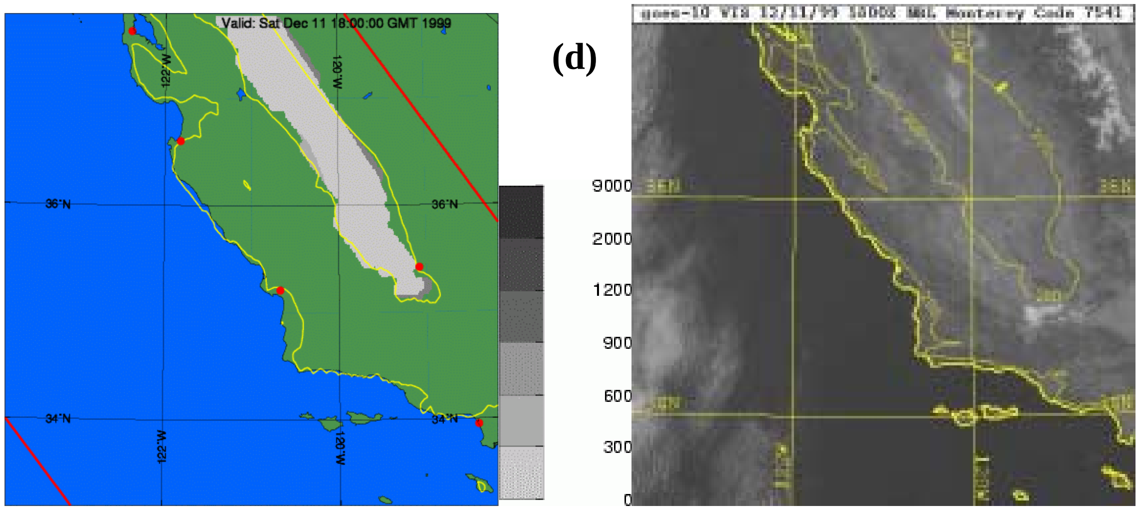


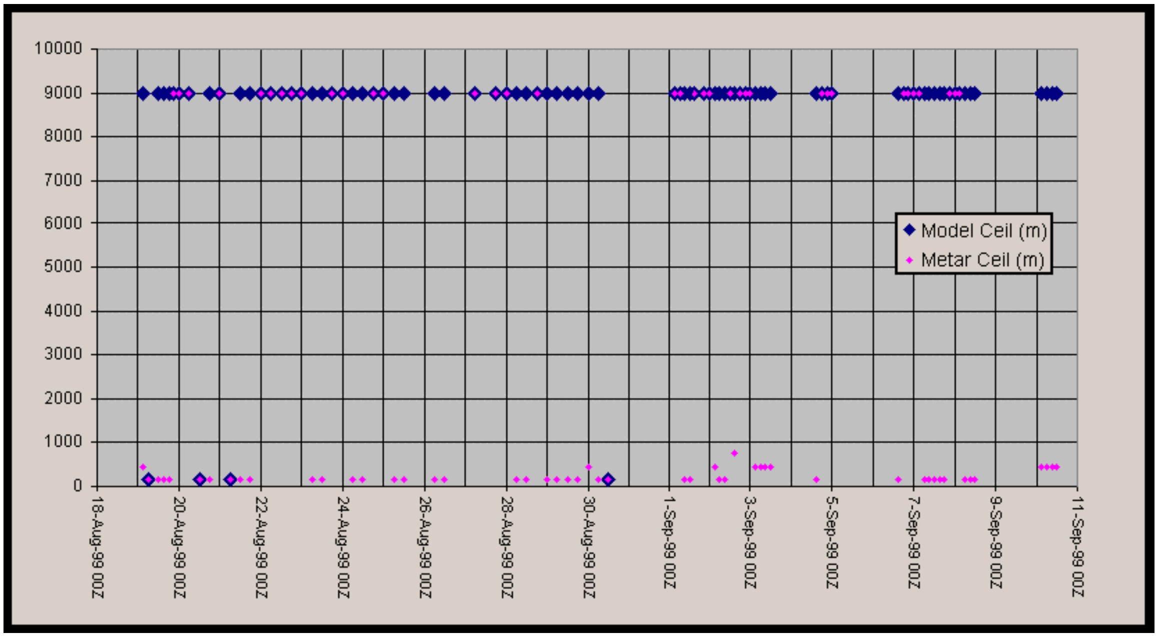
Figure 4. COAMPS Ceiling Height Forecasts and Visible Satellite Imagery
(a) Low Stratus (b) Frontal Passage (c) Cirrus (d) Fog. All ceiling heights are in meters. Red dots indicate station locations. Yellow contours in the forecast images indicate 200 m terrain elevation in the model. Yellow contours in satellite image indicate the actual 200 m terrain height.

During both periods, ceiling heights are consistently over-predicted at KLAX, KMRY, and KSBP and under-predicted at KSFO. KBFL, the only station located away from the coast, correctly predicted unlimited ceiling heights during Period 1; however, Period 2 demonstrated a trend of over-predicting the ceiling height. Similar results at each station were found for visibility. Figs. 5 and 6 compare the forecasts of ceiling and visibility with the METAR observations at KMRY during Periods 1 and 2. Ceiling heights are binned into the layers shown in Table. 1. The levels are chosen to approximate the levels required in aviation applications.

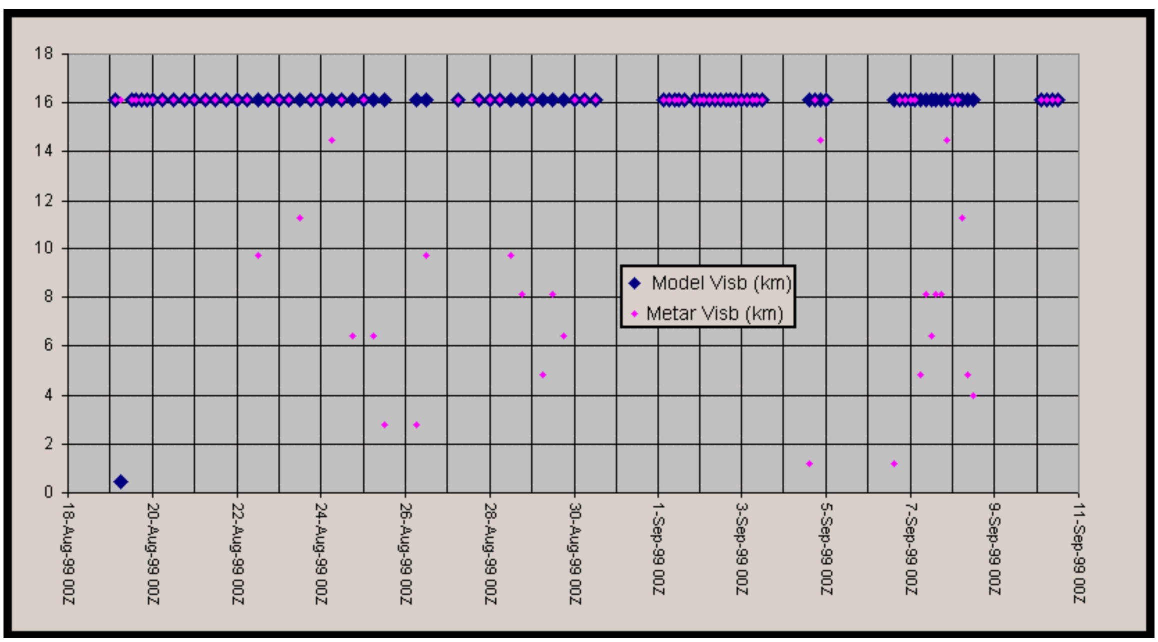
Table 1. Ceiling Height
Values of ceiling height are binned as shown below.

Level 1	$0 \le X < 300$	150
Level 2	$300 \le X < 600$	450
Level 3	$600 \le X < 900$	750
Level 4	$900 \le X < 1200$	1050
Level 5	$1200 \le X < 2000$	1600
Level 6	$2000 \le X < 9000$	5500
Level 7	$9000 \le X$	9000

The ceiling height forecasts and observations in Fig. 5a show a bipolar distribution between unlimited and low ceiling heights. Since the coastal stratus is a few hundred meters in depth with a base at or near the ground surface, ceiling height observations should be expected to be either unlimited (clear skies) or very low (stratus). In most of the cases, the model failed to predict the observed low ceiling heights. The poor forecasts may be a result of the model's inability to accurately predict the timing of the stratus. Another possible explanation is the model topography. The 200 m contour in the model images of Fig. 4 extend beyond the shoreline and differ from the actual 200 m terrain height shown in the satellite images of Fig. 4. COAMPS topography is smoothed using a 25-point filter, and the smoothing of the 4000-5000 ft coastal ranges may act to block the low stratus away from the coastal stations.



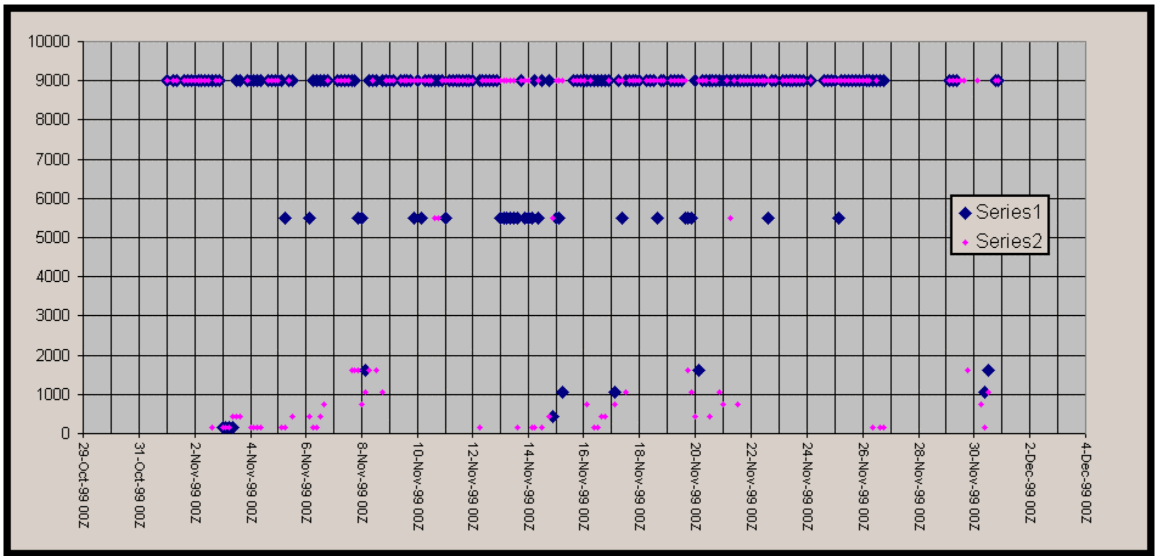
(a)



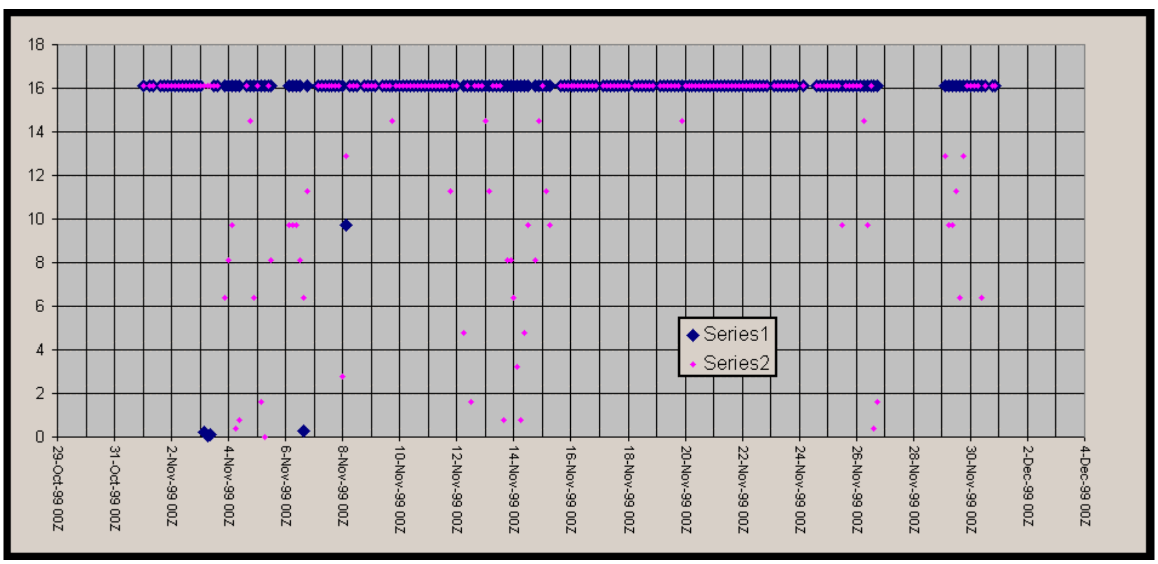
(b)

Figure 5. KMRY Ceiling (a) and Visibility (b) Forecast – Period 1
Blue diamonds indicate model forecasts. Pink diamonds indicate observed (METAR). Ceiling heights are in meters. Visibility is in kilometers.

Unlike Period 1, Period 2 (Fig. 6a) demonstrates more variability among the ceiling height forecasts as expected with the increased frontal activity in the month of November. Forecasts in Period 2 appear to be slightly improved from those in Period 1, but over 50% of the forecasts still disagree with the observations. Interestingly, several values of ceiling height are clustered around 5500 m. The reasons for the clustering are not well understood and should be examined in more detail.



(a)



(b)

Figure 6. KMRY Ceiling (a) and Visibility (b) Forecast – Period 2
Blue diamonds indicate model forecasts. Pink diamonds indicate observed (METAR). Ceiling heights are in meters. Visibility is in kilometers.

Like the forecasts of ceiling height, the visibility forecasts for KMRY (Fig. 6b) also demonstrate little skill. The model forecasted unlimited visibility for all but 5 of the cases in both time periods. Several reasons may account for the model's inability to correctly forecast the visibility. Since aerosols are excluded from the calculation of visibility, obscurants such as haze and smog are not properly represented in the algorithm. For cities such as Los Angeles (KLAX), frequent occurrences of low visibility in the summer are attributed to smog and haze rather than the presence of cloud or rain water. Another potential deficiency with the algorithms is the assumption that a single grid point can represent visibility and ceiling height. Since the grid spacing of the finest mesh is 9 km, visible ranges greater than 4.5 km could not be forecasted without considering the properties of the adjacent grid points.

The effects of using a single grid point can be best quantified by determining the distances that the algorithms "miss" forecasting a low ceiling occurrence. Fig. 7 shows yellow boxes representing a region of 25 (5x5) grid points surrounding three stations where the under-prediction of low ceiling heights was most frequent. In cases where the model incorrectly predicts unlimited ceiling height (> 9 km) at a station, the forecast grid is examined to find the closest grid point where ceiling heights are not unlimited (< 9km). This method treats each ceiling height forecast as either unlimited or restricted. Table 2 indicates the fraction of missed forecasts where the closest correct forecast fell within the yellow boxes shown in Fig. 7.

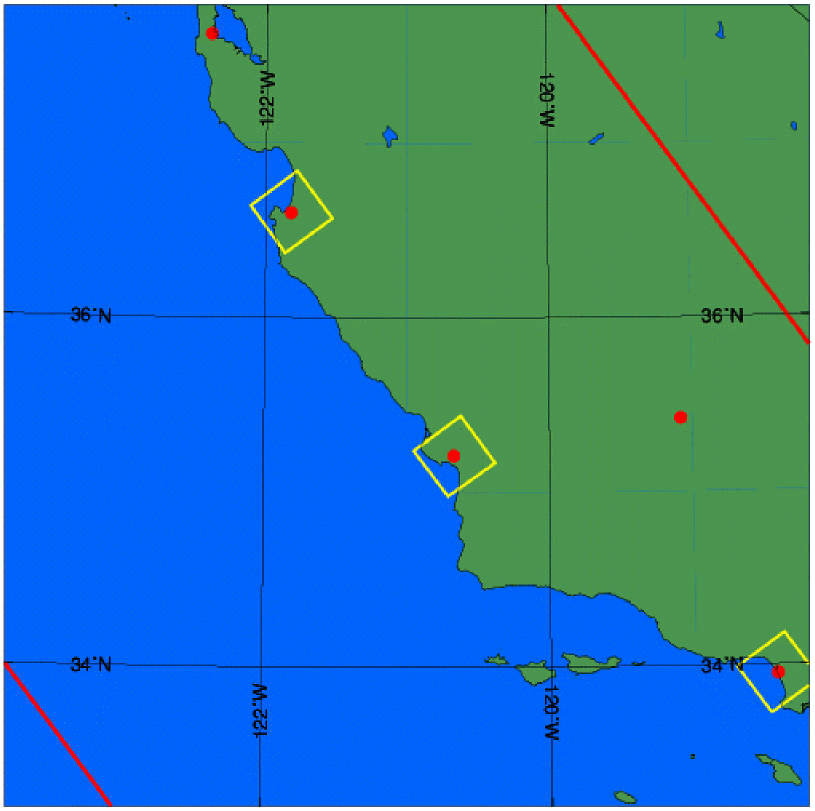


Figure 7. Station Grid Point Boxes
Yellow boxes indicate a 5x5 grid point area.

Table 2. Percentage of Correct Forecasts within a 5x5 Grid Point Box
Parentheses indicate the number of correct forecasts found within the boxes shown in Fig. 7 divided by the total number of misses.

	Period 1	**Period 2**	**Total**
KLAX	47.8% (11/23)	65.6% (21/32)	58.2% (32/55)
KMRY	84.4% (27/32)	62.5% (15/24)	75.0% 42/56
KSBP	87.0% (20/23)	54.5% (12/22)	71.1% (32/45)

Five of the six cases shown in Table 2 were found to have over 50% of the closest "correct" grid points fall within the yellow boxes. A value of 50% means that in 50% of the cases where the model "missed" predicting a low ceiling height, the model missed by <20 km (~2 grid points). The values for KMRY and KSBP (> 80%) during Period 1 are quite remarkable and may be partially attributable to the terrain smoothing described earlier. The closest grid points for the stations were primarily found seaward of the stations.

CONCLUSIONS

A 6-month evaluation of two NCAR C&V algorithms was conducted using successive 12-hour forecasts from COAMPS over the California coast. Comparisons with visible satellite imagery found that COAMPS and the ceiling TA accurately predicted the timing and the shape of the cloud coverage in a variety of synoptic situations. Although comparisons with the METARs at 5 stations demonstrated little skill, considering the ceiling heights of grid points in a 20 km region surrounding each station could make significant improvements to the forecasts.

The visibility TA also demonstrated little forecasting skill when compared with observations. Several factors may have contributed to the poor forecasts of both TAs including a lack of aerosol information, poor representation of the model topography, and the use of a single grid point in each calculation. Like the ceiling forecasts, visibility forecasts may also benefit from an examination of the grid points surrounding each station.

RECOMMENDATIONS

NCAR has plans to modify the visibility algorithm to better reflect aerosol content. Future implementations of the algorithm could incorporate information from surrounding grid points to determine the ceiling and visibility at a given station. In addition, verification efforts must better distinguish between the forecasted fields of the model and the translated fields of the algorithms.

ACKNOWLEDGEMENTS

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