# ASSIMILATION OF SATELLITE DERIVED WINDS IN MESOSCALE FORECASTS OVER HAWAII

T. Cherubini[1], S. Businger[1] C. Velden[2] and R. Ogasawara[3]

[1]UNIVERSITY OF HAWAII
2525 Correa Rd. HIG 367, 96822 Honolulu, HI

[2]UNIVERSITY OF WISCONSIN -CIMSS
1225 W. Dayton St. Madison, WI 53706

[3]SUBARU OBSERVATORY, NAOJ
650 N. Aohoku Pl., Hilo HI 96720

## ABSTRACT

The central Pacific Ocean has a paucity of wind data. Therefore, analyses often poorly represent the atmospheric flow, introducing significant uncertainty in model initial conditions, and resulting in significant forecast errors. This paper presents results from an initial study to assess the impact of Atmospheric Motion Vectors (AMV) derived from geostationary satellite imagery on mesoscale forecasts over the central north Pacific region. These wind observations are derived at CIMSS from tracking clouds and water vapour in sequences of satellite imagery. For a test case, a poorly forecast subtropical cyclone (kona low) that occurred over Hawaii on 23-27 February 1997 was chosen. The Local Analysis and Prediction System (LAPS) was used to assimilate the AMV data and to produce MM5 initial conditions. The satellite wind assimilation is carried out on the 27-km resolution domain covering the central Pacific area. The amount of wind data is greatest in the lower troposphere, with a maximum of about 1500 observations at 900 mb, and in the upper troposphere, with a maximum of about 300 observations at 300mb level. MM5 was run with three two-way nested domains (27, 9 and 3 km), with the innermost domain moving with the kona low. The AMV data assimilation in the MM5 initial conditions was found to increase the cyclonic zonal-wind shear at the upper levels (300 mb) and decrease it in the lower troposphere (850 mb). The AMV data are found to influence the cyclone development, improving the prediction of the cyclone, particularly in terms of position error. AMV data have been operationally ingested by LAPS to produce local high-resolution meteorological analyses since September 2003 at the Mauna Kea Weather Center at the University of Hawaii (http://mkwc.ifa.hawaii.edu). These analyses, in turn, are used as initial conditions for the operational version of MM5. The impact of the assimilation of AMV data on the forecast accuracy of the LAPS-MM5 operational forecasting system will be presented.

## 1 INTRODUCTION

A lack of observational data over the surrounding ocean makes weather forecasting a special challenge in Hawaii. The central north Pacific region that encompasses the Hawaiian Islands is characterized by rapidly evolving mesoscale systems, which compound the forecast challenge. Forecast errors can frequently be traced to errors in initial conditions, particularly in dynamically active areas where observational data are scarce (Klinker et al. 1998). Global temperature and, to some extent, moisture fields from satellite sensors are currently assimilated in global analyses, providing a source of information where conventional data are sparse. However, by comparison global winds are still relatively poorly sampled. Atmospheric Motion Vectors (AMV) are obtained by tracking clouds and water vapour in sequences of geostationary satellite data imagery at the Cooperative Institute for Meteorological Satellite Studies (CIMSS). This study investigates the impact of the assimilation of satellite derived wind data on the accuracy of mesoscale model forecasts over the data sparse central Pacific Ocean. A poorly forecast subtropical cyclone (kona low) that occurred over Hawaii during 23-27 February 1997 was chosen as test case. Details of this storms evolution and impact can be found in Morrison and Businger, 2001 (MB2001 hereafter). GOES-09 AMV data and GOES-09 radiances from three channels (VIS, IR, WV) were available for the period of investigation. This paper will focus primarily on the impact of assimilating AMV data into MM5 initial conditions. Results from the addition of radiance data will be presented for comparison. The implications of these sensitivity experiments for operational forecasting at the Mauna Kea Weather Center (MKWC) will be discussed. The MKWC is a weather research and forecast facility supporting the Mauna Kea observatories (Businger et al., 2002). Since January 1999, the MKWC has issued custom weather forecasts for the astronomy community. The MKWC utilizes forecast guidance from a combination of global models from national operational centres and from a local, dedicated mesoscale numerical modelling effort. The mesoscale model MM5 has been run operationally since January 1999 at the MKWC. Since September 2003 the AMV data have been assimilated into the local analysis and prediction system (LAPS), providing high-resolution initial conditions for twice-daily runs of MM5.

## 2 WIND DATA SET DESCRIPTION

Since 1996 wind data derived from GOES data imagery have been produced at UW-CIMSS (e.g., Neiman et. al 1997 and Velden et. al 1997). An automated procedure provides an estimate of wind at multiple levels using sequences of multi-spectral satellite images. The operational scheme derives wind observations in the visible (VIS) and infrared (IR) window as well as water vapour (WV) absorption bands. Extraction of winds from WV band provides wind data

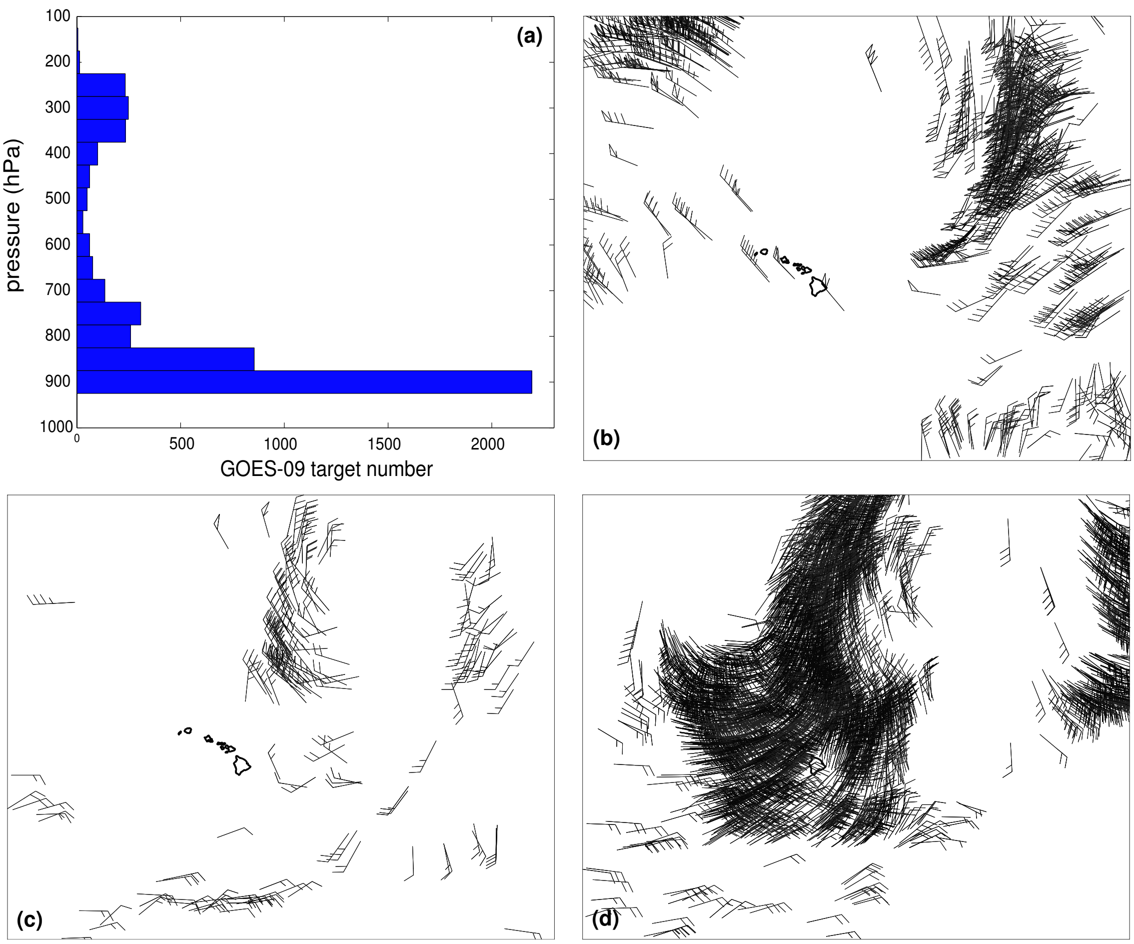


**Figure 1: (a) AMV data distribution with pressure on 23 February 1997. Data are binned every 50 mb. AMV data for 23 February 1997 plotted at (b) 300, (c) 600 and (d) 900 mb.**

in the regions devoid of cloud in the middle-upper troposphere. AMV data are distributed over the entire troposphere but are largely concentrated in the lower troposphere between 900mb and 800mb, with a second maximum at 300mb (Fig. 1a). It is anticipated that data from the upper part of the troposphere will have the largest influence on the system evolution since upper-level forcing has been found to initiate subtropical cyclogenesis (MB2001). The AMV wind data are not uniformly distributed, rather the distribution reflects the locations of clouds and water vapour gradients associated with the developing kona low (Fig. 1b-d).

## 3 DATA ASSIMILATION AND MODEL SET UP

The Local Analysis and Prediction System (LAPS) has been used to assimilate AMV data and to produce local high-resolution analyses (McGinley 1989, McGinley et al. 1991). LAPS was developed at the National Oceanic and Atmospheric Administrations Forecast System Laboratory (NOAA/FSL) to merge all the available data sources over the area of interest and produce coherent analyses of the atmosphere. LAPS performs an analysis of the surface fields first, followed by a wind analysis, a temperature analysis, and finally a cloud-field analysis. All of the above make use of a first guess fields, usually provided by a global numerical weather prediction model. LAPS wind analysis uses all available data sources in a two-pass objective analysis. Background model grids are used as a first guess analysis from which observation residuals are calculated. The observation residuals are subject to quality control (QC) check. AMV data are rejected when the difference between the AMV value and the background model grid is greater than 10 m s-1. The observation residuals are spread vertically onto grid points within 50 hPa of the observations level by means of an exponential weighting term and horizontally using a Barnes exponential weighting function with a radius of influence that is a spatially varying function of the data density. More details about LAPS wind analysis can be found in Albers (1995). For the case under investigation about 6% of the wind data were rejected by the QC check. An average of 4 to 8% of the AMV data gathered at MKWC are rejected by the QC check in the operational analysis making process. Inspection of the rejected wind data does not reveal a coherent signal, rather the rejected data are uncorrelated. Therefore, it is safe to assume that signal is not lost through the QC process.

The mesoscale numerical model used at the MKWC and in this study is the fifth-generation Pennsylvania State UniversityNational Centre for Atmospheric Research (Penn State-NCAR) Mesoscale Model, MM5 (Grell et al. 1995). MM5 is a non-hydrostatic primitive equation model with a terrain following coordinate. It has multiple nesting capabilities to enhance the simulation over the area of interest. A configuration of three two-way nested domains was chosen for the case study presented in this paper (Fig. 2). The horizontal resolution is 27 km for the domain covering the central Pacific area, 9 km for the nested domain and 3 km for the innermost domain, which is enabled to move along with the kona low. Thirty-three sigma levels denser in the lower troposphere are used with the top level at 100mb. The MM5 physics package used includes: the grid resolvable Reisner-2 moisture scheme (Reisner, 1998) that includes graupel and ice condensation nuclei and allows coexistence of mixed water phases; the Kain-Fritsch cumulus convection scheme (Kain and Fritsch, 1990); a high-resolution MRF boundary layer scheme (Throen and Mahrt, 1986); a long-wave/short-wave radiation scheme that allows interaction with water vapour, clouds, precipitation and the surface (Stephens 1978, Garand 1983).

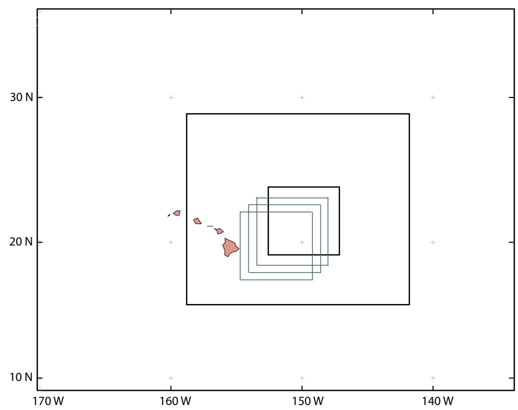


**Figure 2**: **MM5 domains configuration: the innermost domain moves with the kona-low system.**

When data assimilation is not performed, medium-range Global Circulation Model (GCM) analyses provide the initial conditions for MM5 over the domain of interest. Operationally, the MM5 boundary conditions are updated every 6 hours using the GCM forecast from the analysis used to build the initial conditions. In order to have the best simulation possible for the case study under investigation the experiments described hereafter are carried out in archived mode: boundary conditions are produced using the GCM analyses (not the forecasts). ECMWF Re-Analysis data, thereafter referred as ERA-40, have been used for the case under investigation. The ERA-40 analyses have spectral resolution T159, corresponding to $\sim$ 125 km horizontal resolution in the tropics, and are available on 60 vertical levels.

Four sensitivity experiments are carried out with MM5, using four different sets of MM5 boundary and initial conditions.

1. MM5 initial and boundary conditions are created using ERA-40 valid at 18:00 UTC, 23 February 1997. Model results associated with this set of analyses will be referred to as the Control Experiment.

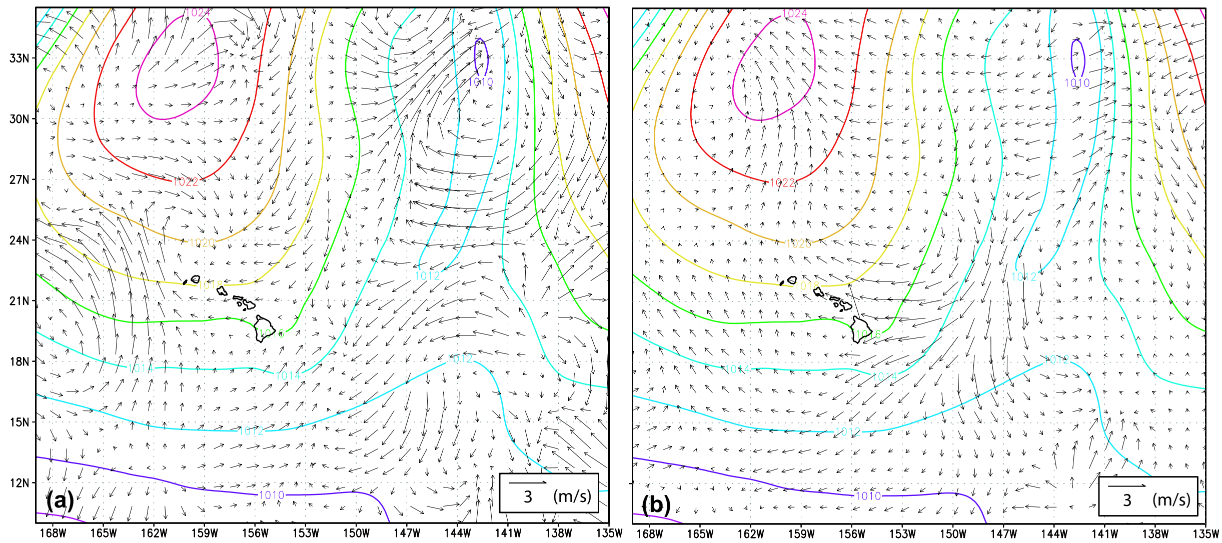


**Figure 3: Vector difference between Experiment 2 initial conditions and Control Experiment initial conditions on 23 February 1997 at 300mb (a) and 900mb (b). Mean seal level pressure is overlapped as a reference.**

2. AMV data for 1800 UTC on 23 February 1997 are assimilated through LAPS into MM5 initial conditions. MM5 boundary conditions are updated using ERA-40 only. Analyses and model results associated with this set of analyses will be referred to as Experiment 2.

3. AMV data are assimilated through LAPS into MM5 initial and boundary conditions throughout the model run. Analyses and model results associated with this set of analyses will be referred to as Experiment 3.

4. AMV and radiance data for 1800 UTC on 23 February 1997 are assimilated through LAPS into MM5 initial conditions. MM5 boundary conditions are updated using ERA-40 only. Analyses and model results associated with this set of analyses will be referred to as Experiment 4.

Looking at the vector-difference wind fields, positive anomalies are primarily located along the west side of the trough at the surface and negative anomalies are found on the east side of the trough at 300mb (Fig. 3a). At 900mb positive anomalies are primarily located along the east side of the trough at the surface and negative anomalies are found on the west side of the trough, (Fig. 3b).

Divergence fields derived from the initial analyses for Experiment 2 and the Control Experiment exhibit noticeable differences in both the lower and upper atmosphere (Fig. 4). Fig 4a shows positive divergence located on the east side of the trough at 300 mb. Divergence residuals show negative values on the east side of the trough, indicating that the area of divergence aloft is reduced when AMV data are included in the analysis. In the lower atmosphere (900 mb) the area of convergence is reduced when AMV data are included in the analysis (Figs. 4c and 4d).

## 4 RESULTS OF SENSITIVITY EXPERIMENTS

MB2001 show the importance of upper-level divergence in kona low evolution. The results of the sensitivity experiments can be interpreted with reference to the changes in divergence associated with the assimilation of AMV and radiance data in the analyses. The model is able to capture the deepening trend of the kona low significantly better than the NCEP AVN forecasts, but the predicted values are not as low as estimated from subjective analysis (Fig. 5). When the data assimilation takes place at the initial time only (Experiment 2), the impact of assimilated wind is greatest during the first six hours of simulation, and the impact tends to diminish as the simulation time increases (Fig. 5 red line). It is interesting to notice how the use of AMV data through the all simulation period (Experiment 3) produces a deeper pressure minimum particularly for the last 40 hours of simulation (Fig. 5 blue line). However, slightly higher values of the minimum central pressure than were expected are seen in the 12 hours between 06 and 18 UTC on 24 February. The best values for the pressure minimum during the first 30 hours of simulation are found when radiances and AMV data are used in the model initial conditions. A better picture of the moisture distribution given by the cloud physics analysis results in a faster deepening rate, particularly in the early stages of cyclogenesis,

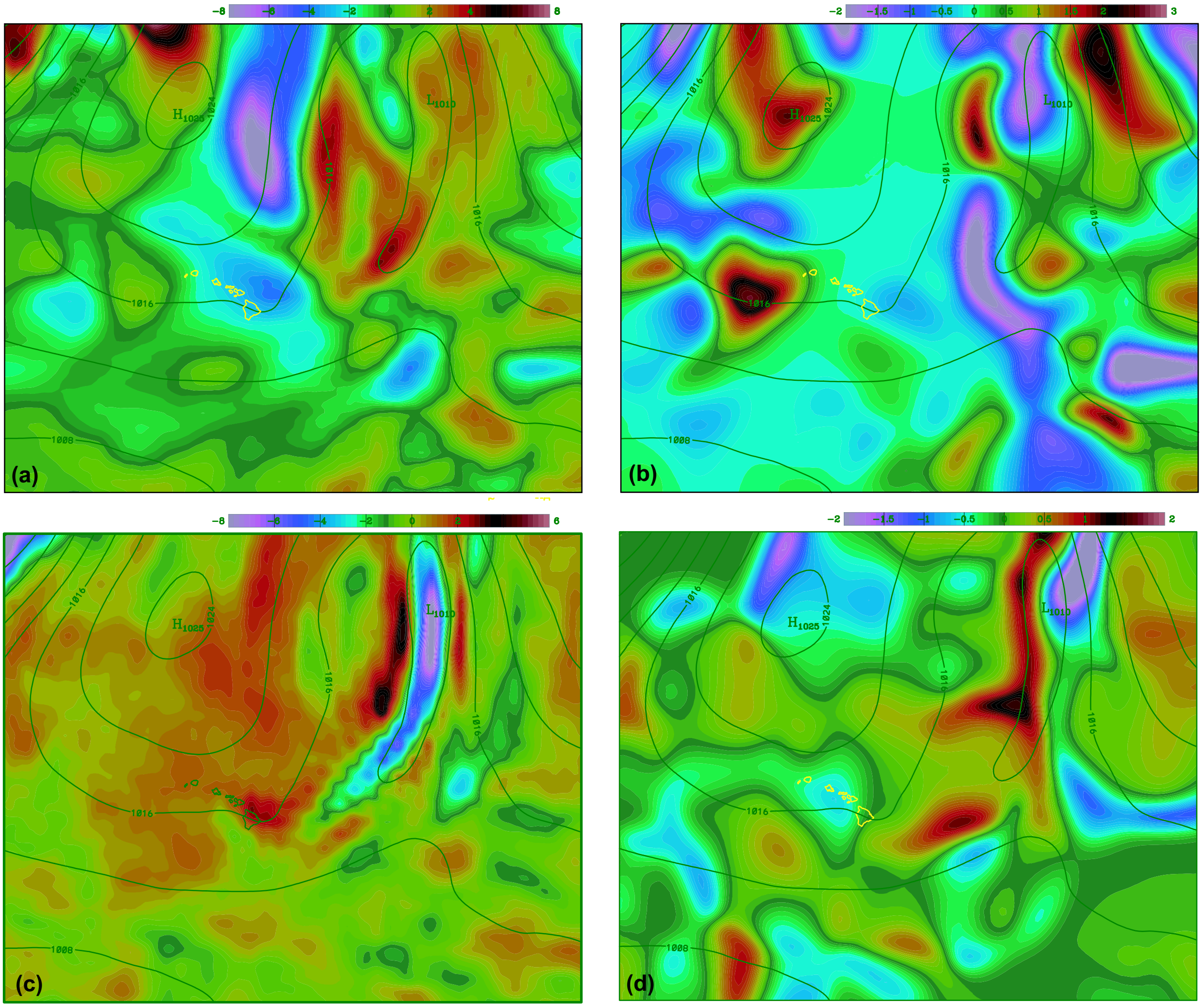


**Figure 4**: **Initial analysis of 300-mb divergence for Experiment 2 and (b) 300-mb divergence residual (Experiment 2 divergence Control divergence). (c) Initial analysis of 900-mb divergence for Experiment 2 and (d) 900-mb divergence residual.**

confirming the importance of latent heating in addition to dry dynamics for an accurate simulation. The underestimation of the lowest central pressure by the simulations may be due in large part to the fact that the central pressure of the initial disturbance was underestimated by the initial analysis (compare dashed and solid black lines in Fig. 5b).

Better agreement between observed and modelled storm tracks is seen during the first 24 to 30 hours of simulation when AMV data are included in the model initial conditions (Experiment 2) (Fig. 6). Both the control and Experiment-2 simulations show excursions in the storm track during the last hours of the simulations that were not observed as the kona low approaches the island of Hawaii. The track from the simulation in Experiment 3 (blue line) exhibits a much smoother track that is closer to the observed track.

MM5 tends to accelerate the kona low system during the intensifying stage in the Control Experiment. Additionally, the simulated system shows evidence of weakening during the mature stage. The inclusion of AMV data in the model initial conditions (Experiment 2) slows down the system evolution during the intensifying stage, likely because of the decrease in the divergence aloft and decrease of the convergence in the lower atmosphere at the initial time of the simulation. The impact of AMV data vanishes $\sim$ 24 hours into the simulation, and weakening characterizes the mature stage. The inclusion of AMV data in both the initial and boundary conditions (Experiment 3) leads to slower intensification early in the simulation; however in the latter part of the simulation, better simulations are produced for track and minimum central pressure. Experiment 4, in which both AMV and radiance data were assimilated, provides the best results in terms of location errors for the first 24/30 hours of the simulation. The weakening trend during the mature stage seen in this experiment is due in part because the data assimilation only occurred at the initial time.

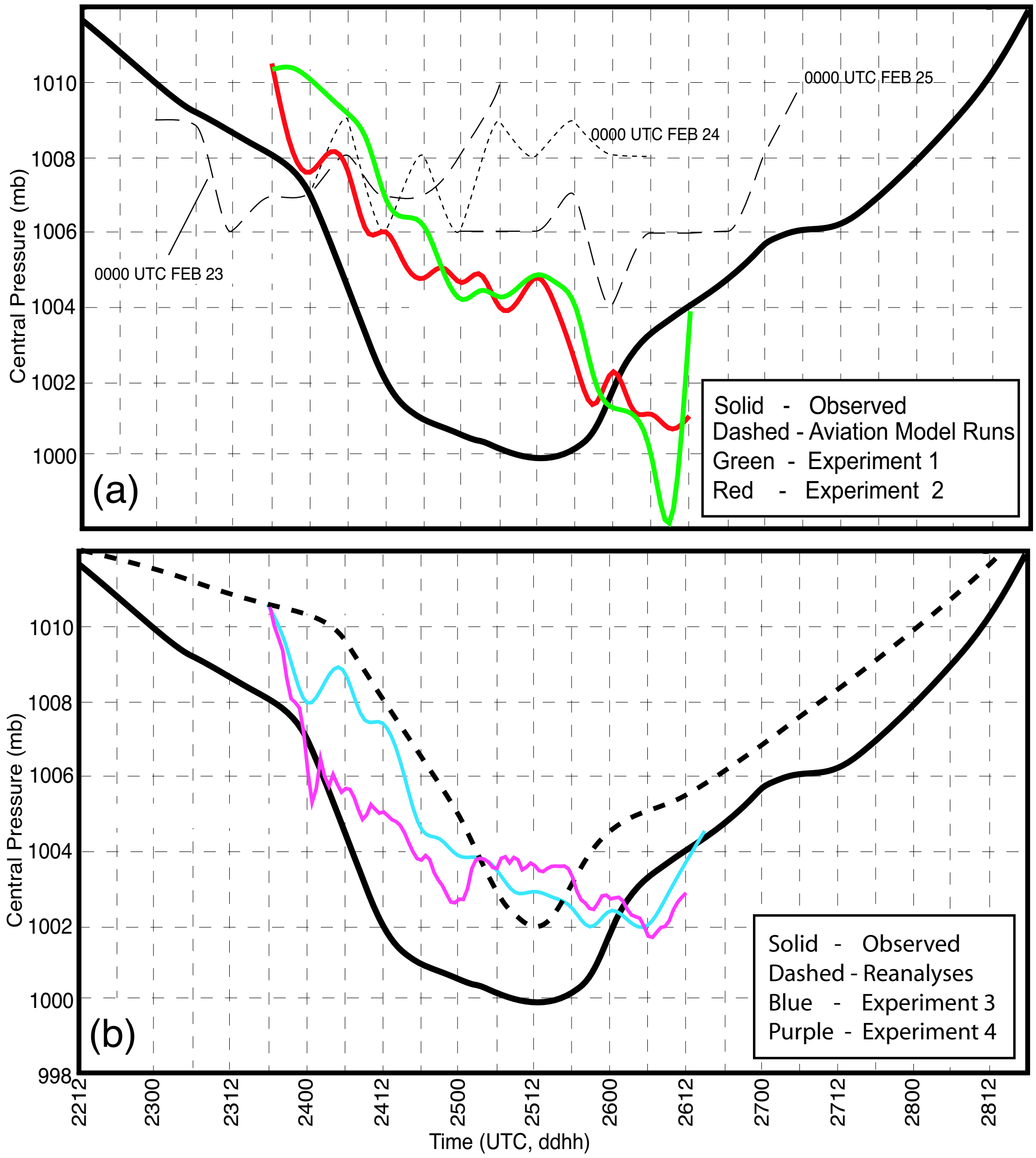


**Figure 5**: **shows the time series of kona low central pressure as from the observations and experiment results. (a) The solid black line is the subjective analysis from MB2001. Thin dashed lines are from NCEP AVN simulations at labelled starting times. The green solid line shows the MM5 Control simulation. The red solid line shows the central pressure development when AMV data are included in the MM5 initial conditions only (Experiment 2). (b) The blue line is the central pressure evolution when AMV data are used in the model boundary conditions during the whole simulation period (Experiment 3). The purple line shows the central pressure evolution when GOES-09 radiances are included in the model initial conditions (Experiment 4).**

## 5 IMPACT OF AMV AND RADIANCES ON MKWC FORECASTS

AMV data have been obtained at MKWC and operationally assimilated into LAPS since September 2003. In addition to the AMV data, LAPS operationally assimilates all available synoptic and maritime data, two soundings, and radiances from 3 GOES-10 channels (IR, VIS, VW). Analyses verifying at 00, 06, 12, and 18 UTC are produced daily and used to initialize two daily MM5 runs (00 and 12 UTC). These MM5 forecasts with full LAPS input are run in parallel with two MM5 runs without LAPS input. NCEP Global Forecasting System (GFS) analyses and forecasts serve as the initial and boundary conditions for these comparison runs. Finite computational resources preclude a third set of operational runs initialized only with AMV data. Therefore, the results in this section compare MM5 forecasts run with and without the full LAPS data assimilation in the initial conditions. The number of AMV data ingested

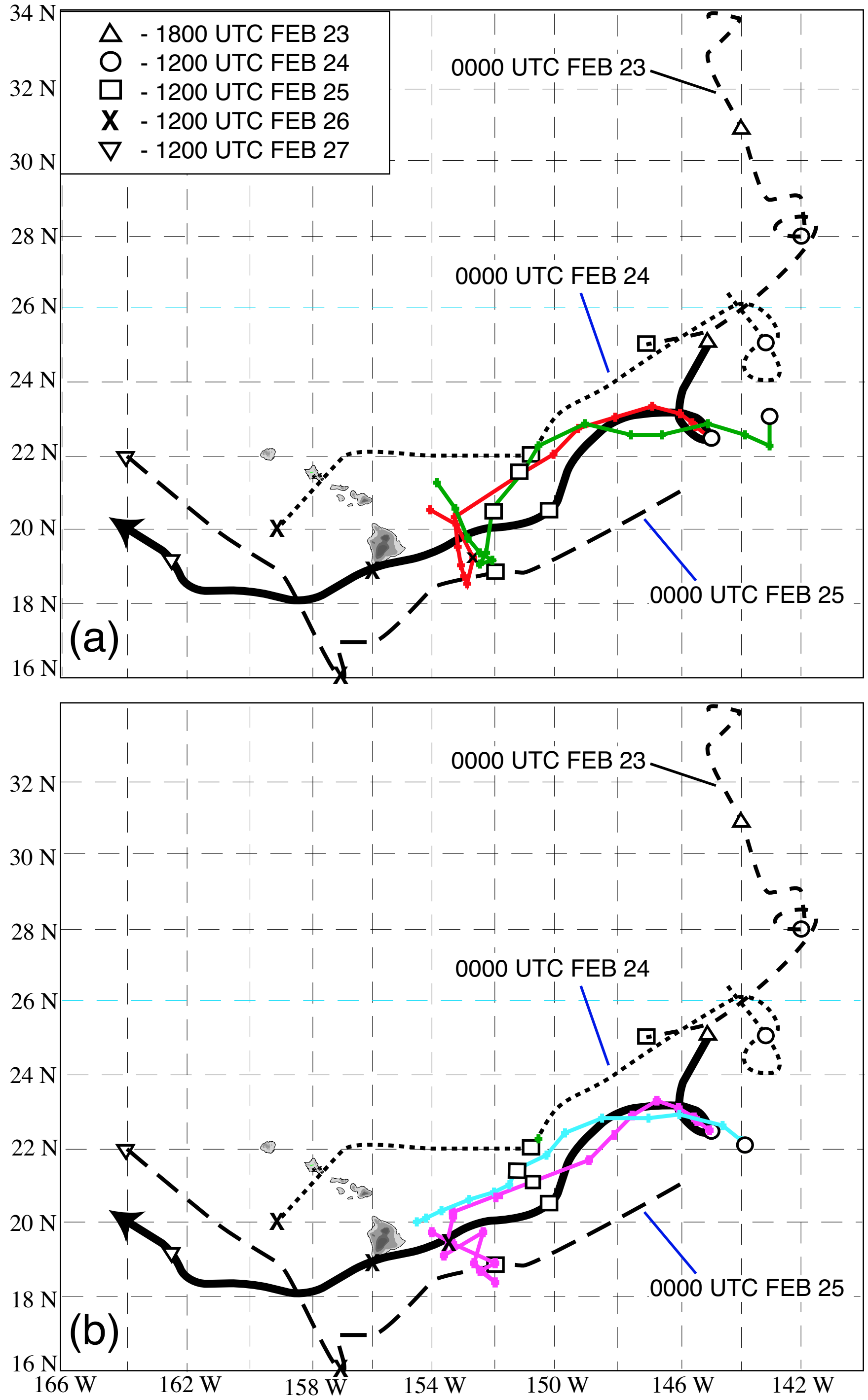


**Figure 6**: **Comparison of the storm track for the subjective analysis from MB2001 (solid black line) and results from the four sensitivity experiments. (a) The green and red lines show the system tracks from Experiment 1 and 2, respectively. (b) The blue line is the track from Experiment 3; the purple line represents the system track from Experiment 4.**

into LAPS varies from day to day depending on environmental conditions (Fig. 7). The two distributions strongly differ because GOES-10 visible channel is not available at 12 UTC. Although AMV are distributed throughout the troposphere, they show a bimodal distribution. The 850 mb peak is associated with the tracking of low-level clouds in the visible channel. The 250-mb peak comes from tracking clouds in both the visible and infrared channels. Given the high number of AMV data available, compared to any other wind data gathered into LAPS (synoptic stations and two soundings) they have the higher weight in the analysis. GOES-10 radiances contribute primarily to the moisture

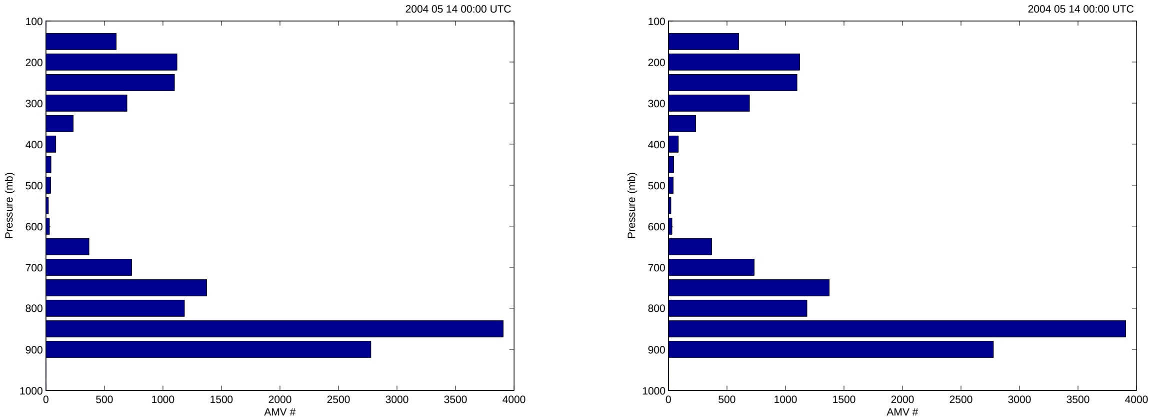


**Figure 7**: **Average vertical distributions of AMV data that pass LAPS quality control, binned every 50 mb, for (a) 1200 UTC and (b) 0000 UTC.**

field in the analyses.

The verification period covers February and March 2004. The verification procedure is based on the calculation of root mean square errors (RMSE) for select MM5 fields at increasing forecast times. The RMSE is calculated comparing mean sea level pressure, temperature, relative humidity and winds components at 850mb, to the NCEP GFS analyses verifying at the forecast time (See Fig. 8). Data used in the verification process cover the model domain that extends from 5N to 35 N and from 140W to 17W. This verification approach is a model grid point to analysis grid point as opposed to a model grid point to observation location verification approach. Given the paucity of synoptic observations in the central pacific area, the first approach is preferred since it provides larger samples on which to run the statistical analyses. The ideal verification procedure encompasses both methodologies. A drop in the RMSE is evident on the first 24 hours of simulation, when LAPS is used in the model initial conditions (Fig. 8). The reduction in error is larger for the 00 UTC forecast cycle than for the 12 UTC cycle. This difference may be due to the lack of visible channel data at 12 UTC over the central Pacific, which impacts both radiance and AMV data.

In the following discussion we will focus on the $t_0$+12h verification time only. Output from forecasts with a starting time of 00 UTC ($t_0$) is evaluated, to focus on the time when the impact of the LAPS data assimilation may be greatest. The RMSE for the MM5 12-hr forecasts initialized with LAPS (solid line) were consistently smaller than the RMSE for MM5 forecasts initialized without LAPS (thin dashed line) for most of the fields analyzed (Fig. 9). The largest impact was seen in the sea-level pressure and relative humidity fields. The temperature field shows less impact from data assimilation, consistent with that fact that temperature is better diagnosed in the GFS analyses.

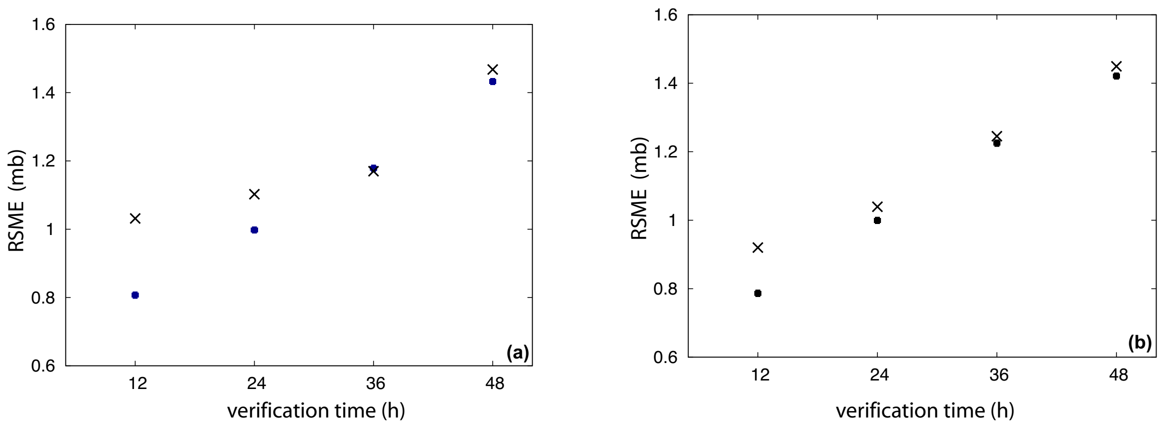


**Figure 8**: **Mean sea-level pressure (mb) RMSE at four different verification times ($t_0$+12h, $t_0$+24h, $t_0$+36h, $t_0$+48h) averaged over all grid points and over the verification period (Feb-Mar). Dots represent RMSE from MM5 forecasts initialised with LAPS analyses and crosses are RMSE values from MM5 forecasts without LAPS. Results from runs initialized at (a) 00 UTC and (b) 12 UTC, respectively.**

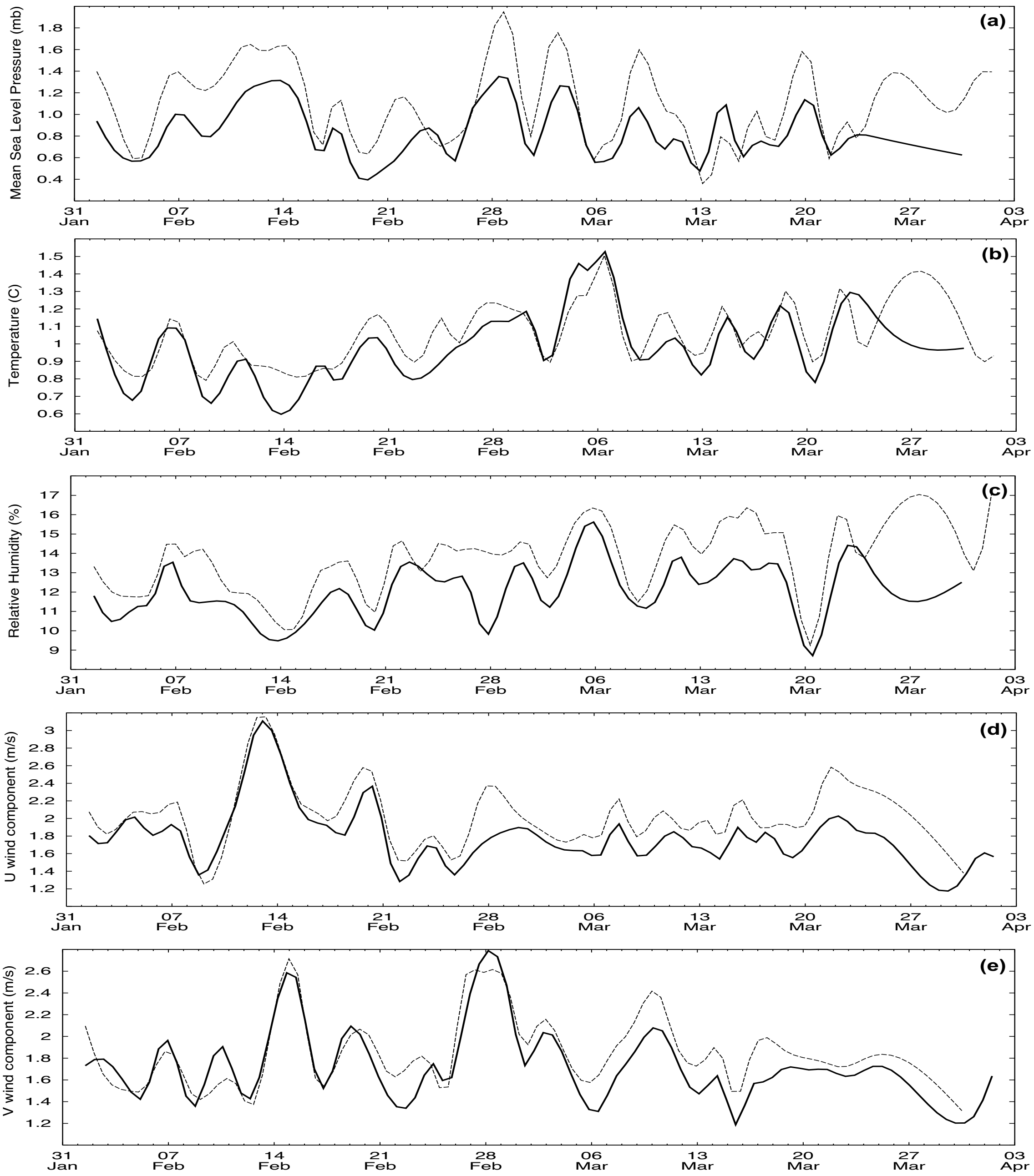


**Figure 9**: **Time-series of RMSEs for (a) mean sea level pressure and (b) temperature, (c) relative humidity, (d) u and (e) w components at 850 mb. Solid lines refers to 12 hours forecast values from MM5 initialised with LAPS at 00 UTC; shaded thin lines refer to 12 hours forecast values from MM5 without LAPS at 00 UTC.**

For forecasts with a 12 UTC starting time the impact of using LAPS on RMSE is smaller than was found for the 00 cycle, but it was still positive (not shown).

## 6 CONCLUSIONS

AMV data provide a great opportunity to improve the knowledge of the atmospheric flow over data sparse regions, particularly over open oceans. In this paper we show that application of a simple procedure to assimilate AMV data into MM5 initial conditions has verifiable positive impact on the simulation accuracy. A poorly forecast sub-tropical cyclone was chosen for a series of sensitivity experiments. Simulations with and without assimilation of AMV data in the model initial condition were conducted. The results show that the added information on the model flow provided by AMV data, contribute to a reduction in the system track error. Moreover, a better agreement is found between the surface subjective analysis and the model surface fields. More data assimilation experiments including radiances from GOES-09 IR, WV and VIS channels in the model initial conditions have been performed to investigate the role of the moisture in the subtropical cyclogenesis. A more accurate knowledge of the moisture distribution in the model initial conditions plays an important role as well. Given the correlation between dynamic and thermodynamic processes, the synergic use of wind and radiance data provides the best simulation. Since September 2003, AMV data are part of the data gathered at MKWC and are operationally assimilated into LAPS along with synoptic observations, two soundings and radiances from three GOES-10 (IR, WV, VIS) channels. A MM5 forecast initialized with LAPS analyses and a MM5 forecast initialised using the GFS analyses only as initial conditions are each run twice daily. The initialization times are 00 and 12 UTC. The model performance as a function of the initial conditions used has been compared through analysis of the model RMSE for select fields. A positive impact from using a local assimilation system is found. It is reasonable to attribute this positive result to satellite data (both radiances and AMV) since they provide the greatest contribution to the LAPS analyses, given the relatively data sparse ocean surrounding Hawaii. The results of the sensitivity experiments presented in this paper depend on the data assimilation procedure. This work is intended to provide a simple evaluation of forecast sensitivity to additional wind data in the model initial conditions. Future efforts will be directed toward implementation of a more complex assimilation system, such as three and four Dimensional Variational analyses (3DVAR, 4DVAR). However, these are computationally expensive and will require additional resources. AMV data are provided with a quality indicator (QI) flag for each observational datum, which is an independent measure of quality that can be used in the assimilation process (Holmlund, 1998). Sensitivity simulations using the provided QI will included in the future studies.

## 7 AKNOLEDGMENTS

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