Hawaiian Atmospheric Forecasting Utilizing the Weather Research and Forecast Model

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ABSTRACT

The Hawaiian Islands consist of large terrain changes over short distances, which results in a variety of microclimates in a very small region. Some islands have rainforests within a few miles of deserts; some have 10,000+ feet summits only a few miles away from the coastline. Because of this, weather models must be run at a much finer resolution to accurately forecast weather changes in these regions. National Center for Atmospheric Research's (NCAR) Weather Research and Forecast Model (WRF) is run, on a nightly basis, using a coarse 54 km resolution grid (encompassing an area of approximately 7000 by 7000 km) nested down to a 2 km grid over each Hawaiian county. Since the computational requirements are high to accomplish this in a reasonable time frame (as to still be a forecast) WRF is run in parallel on MHPCC's Cray 2.4 GHz Opteron based Linux system, "Hoku". Utilizing 32 nodes (64 processors) the WRF model is run over the above conditions in approximately 4 hours.

Although WRF forecast have only been in place for less than a year now, a lot of experience has gone behind its setup. MHPCC has been running the National Center for Atmospheric Research's Mesoscale Model version 5 (MM5) since 2000, which continues to be utilized by operators at the telescope facilities on Haleakala, Maui. Currently, the forecast produced is for a 48-hour simulation, but will most likely be extended to a 72-hour simulation; this forecast is available to operators by 8 AM and produces forecasts out until the next day at 8 PM. This is enough time to give operators and managers time to reschedule their operations if unacceptable conditions are predicted. The products we currently provide are: temperature, wind speed & direction, relative humidity, and rainfall. Additional products are in production, including a measure of optical turbulence for the telescope operators.

1. MOTIVATION

The telescope operations on Haleakala are highly dependent on weather conditions on the Hawaiian Island of Maui. If the wind speed is too high then the telescopes cannot be utilized. Problems also exist if there are clouds or optical turbulence. Rainfall and relative humidity are also a factor in determining the capabilities of the telescopes. In order to effectively schedule telescope operations, an accurate weather prediction is extremely valuable. Current forecasts that are available from the National Weather Service (NWS) give good indications of approaching storm fronts but only at the coarse level (30-50 km resolution). Because of the location of the telescopes on Maui, this can be insufficient for their needs.

The additional benefit of having access to an accurate forecast is that they can perform some operational scheduling for the telescope facilities. For example, if unacceptable weather conditions are predicted, they can plan maintenance. This allows the facility to function more effectively by saving them time and ultimately operating expense.

2. NUMERICAL WEATHER MODELING

The numerical weather model (NWM) used for this project is the Weather Research and Forecasting (WRF) Model [1,2]. It was chosen because it has many desirable features:

(a) Multiple nested grid capability,
(b) Excellent data assimilation capabilities (WRF 3DVAR [3]),
(c) Excellent GUI to prepare standard initialization for WRF model (WRFSI [4]),
(d) The model is capable of being run in parallel on MHPCC'S Opteron cluster,

The nested grid capability allows a coarse grid to be run over a large area (of less interest, such as the open ocean) in less compute time while still being able to operate using finer grids on smaller area (of great interest, such as the Hawaiian islands), rather than using a fine grid over a very large area at a high computation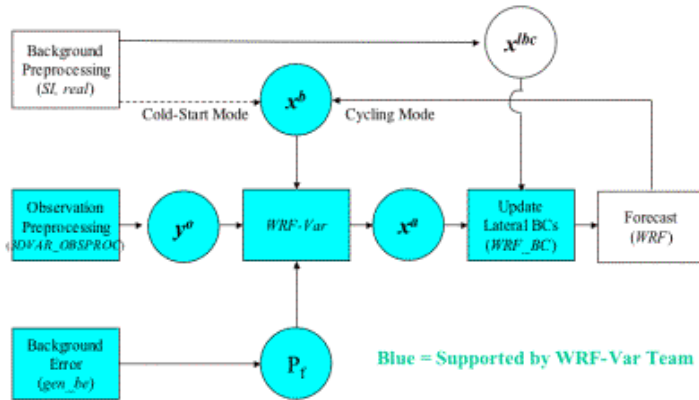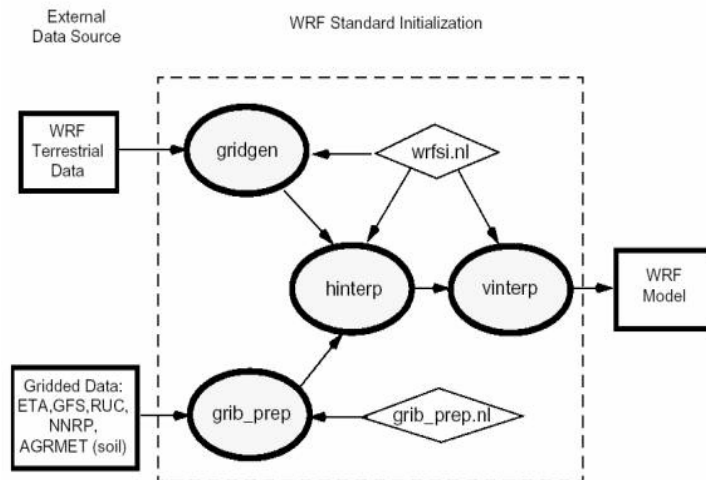al cost. The ability of WRF 3DVAR (Three Dimensional Variational) data assimilation (see Figure 1 for flowchart) to include observational data allows the model to start with a better "first guess", which in turn allows the model to "spin up" quicker. The WRF Standard Initialization (WRFSI) is the first step to set up the model for real data simulations. WRFSI is a collection of four programs (see Figure 2) that together produce the input data necessary for the WRF model to be run. Finally, the ability for the model to be run in parallel is important because it allows the production of high-resolution output in a reasonable time frame (when the forecast produced by the WRF simulation is still a prediction). Benchmarks have been done for the parallel version of WRF (using Message Passing Interface (MPI)), but it is not easy to make a fair comparison since the simulations domains are significantly different and more complex than NCAR's choice of domains (See the WRF model's parallel performance at http://www.mmm.ucar.edu/wrf/WG2/bench).
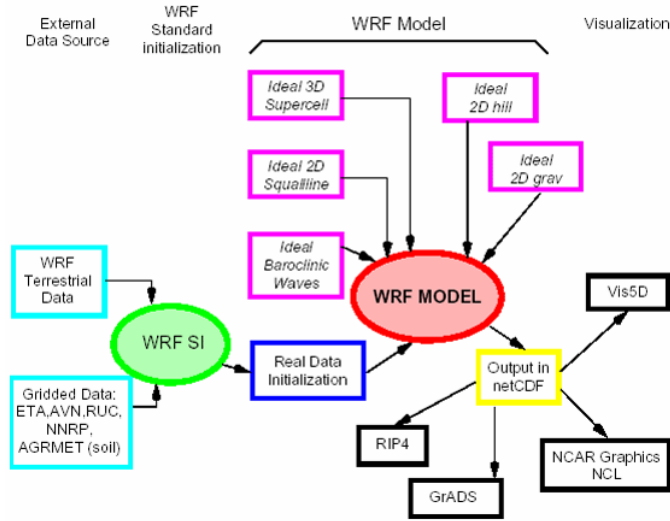

Figure 1: WRF-Var Flowchart

Figure 3: WRF Modeling System

The best way to understand how the WRF model operates is to explain the main routines it uses to accomplish a numerical simulation. Figure 3 is a flow chart of the main routines used in the WRF model. The WRFSI collection of programs defines a simulation domain, reads and interpolates the various terrestrial datasets from latitude and longitude grids to the projection grid, and lastly to degrib and interpolate meteorological data from another model to this simulation domain. The terrestrial inputs include terrain, landuse, soil type, annual deep soil temperature, monthly vegetation fraction, maximum albedo, and slope data. The WRF Model, composed of several packages, is capable of being run in parallel. The WRF model is a fully compressible, nonhydrostatic model (with a hydrostatic option). Its vertical coordinate is a terrain following hydrostatic pressure coordinate. The grid staggering is the Arakawa C-grid. The model uses the Runge-Kutta 2nd and 3rd order time integration scheme, and 2nd to 6th order advection schemes in both horizontal and vertical directions. It uses a time-split small step for acoustic and gravity wave modes. The dynamics conserves scalar variables. Lastly, the output model data is in a netCDF format; this data can be configured to be output at a user specified time (i.e. every three hours, on the hour, every 30 minutes, etc.). It can essentially be displayed using any tool capable of displaying this data format. Currently four post-processing utilities are supported, NCL, RIP4, WRF2GrADS (for use with GrADS) and WRF2VIS5D (for use with VIS5D).

3. SETUP AND AREA OF INTEREST

The WRF model is a fully compressible, non-hydrostatic model (with a hydrostatic option) utilizing terrain-following sigma vertical coordinates. In this simulation we will use:

1. 55 sigma levels from the surface to the 10-millibar (mb) level with a bias towards levels below a sigma of 0.9 (close to the surface). High vertical resolution is needed at the lowest levels to resolve the anabatic flow, katabatic flow and nocturnal inversion in the near surface layer [5,6].
2. The Betts-Miller-Janjic cumulus parameterization scheme [7] is used for the 54 and 18 km resolution domains. For the rest of the finer resolution domains no parameterizations are used. It is an appropriate parameterization scheme for this level of resolution.
3. The Mellor-Yamada-Janjic Planetary Boundary Layer (PBL) scheme [7] for all domains. It is a one-dimensional prognostic turbulent kinetic energy scheme with local vertical mixing.
4. The Monin-Obukhov (Janjic Eta) surface-layer scheme.

5. Eta similarity; based on Monin-Obukhov with Zilitinkevich thermal roughness length and standard similarity functions from look-up tables.
6. The RRTM (Rapid Radiative Transfer Model) for longwave radiation. An accurate scheme using look-up tables for efficiency. Accounts for multiple bands, trace gases, and microphysics species.
7. The Dudhia scheme for shortwave radiation. A simple downward integration allowing efficiently for clouds and clear-sky absorption and scattering.
8. A 5-layer soil ground temperature scheme. Temperature is predicted in 1, 2, 4, 8, and 16 cm layers with fixed substrate below using the vertical diffusion equation.
9. Ferrier (new Eta) microphysics. The operational microphysics in NCEP models. A simple efficient scheme with diagnostic mixed-phase processes.

Since this prediction is intended for the operators of the telescopes on Haleakala, the area of interest is the Hawaiian Islands. Since storm systems miles away can affect the Hawaiian Islands, the prediction must include a long range forecast. The Hawaiian Islands contain a variety of microclimates in a very small area. Some islands have rainforests within a few miles of deserts; some have 10,000+ feet summits only a few miles away from the coastline. Because of this, the model must be run at a much finer resolution to accurately predict these areas. To satisfy both requirements, a nested grid approach must be used. The WRF model uses a conventional 3:1 nesting scheme (although ratios of 2,3,4, and 5 could be used) for two-way interactive domains. This allows the finer resolution domains to feed data back to the coarser domains. The largest domain covers an area of approximately 7000 km by 7000 km at a 54 km grid resolution. It is then nested down to 18 and 6 km around the Hawaiian Islands and then down to 2 km for each of the 4 counties.

4. DAILY OPERATIONS

Every Night at Midnight Hawaiian Standard Time (HST), a PERL script is run to handle the entire operation necessary to produce a weather forecast and post it to the MHPCC web page (http://weather.mhpcc.edu). The procedures the script executes are:

1. Determine and download the latest global analysis files from NCEP for a 48-hour simulation,
2. Begin processing by sending these files through WRFSI,
3. Take the output data files and input them into WRF's real.exe,
4. Submit the WRF run to MHPCC's Cray 2.4 GHz Opteron Linux System ("Hoku") for execution
5. Average daily run requires from 3.75 to 4.00 hours for completion on 64 processors (32 nodes),
6. Data is output in 1-hour increments,
7. Data is processed in parallel to create useful images for meteorological examination (utilized RIP),
8. Convert images to a web viewable format (from CGM to PNG graphic files),
9. Create the web pages these images will be posted on,
10. Post web pages and images to MHPCC's web site.

Most of these stages are self explanatory, but some require additional information. Step 1, can require some time as the script is downloading 9 distinct, 24 to 26 MB, global analysis files from NCEP. This can affect the time it takes for the entire process to complete as the download time can vary based on the NCEP ftp site, web congestion, and MHPCC's connectivity. In addition, the data is posted to the NCEP ftp site starting at 11 P.M. (HST) and complete any time from 11:45 P.M. to 12:00 P.M. (HST); hence the script is setup with a means to check the "freshness" and completeness of the files to be downloaded. Step 4, job submission, is handled through a standing reservation for 32 nodes (64 processors) starting at 1 A.M. (HST). This ensures that the model will be run and completed at a reasonable time in the morning. Step 7, data processing, includes the choices of fields to be output to the web. Current choices are:

temperature, wind speed & direction, relative humidity, and rainfall. A more detailed description is given below:

1. Surface temperature (in degrees Fahrenheit): This field provides the temperature at 2 meters.
2. Surface wind (Knots): The wind speed in knots at 10 meters.
3. Relative Humidity (% with respect to water): This field provides the relative humidity at the lowest sigma level (.99). Sigma of .99 conforms to an Elevation of 96 meters (315 ft) above sea level (see Figure 4 to visualize the terrain conforming sigma levels).
4. Rainfall: This plot has the accumulated model rainfall over the past hour before the specified time. The rainfall is in mm (1 in = 25.4 mm).
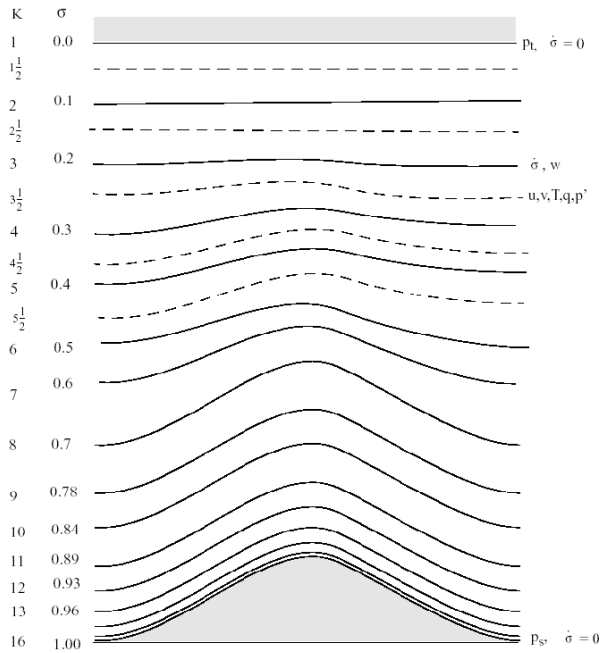
Figure 1.2 Schematic representation of the vertical structure of the model. The example is for 15 vertical layers. Dashed lines denote half-sigma levels, solid lines denote full-sigma levels.

Figure 4:Sigma terrain conforming

Additional capabilities have been added to the process of obtaining the forecasts [8]. They include:

1. Highly reliable (fault tolerant) scripts that allow for quick changes
2. Script will retrieve the most recent pre-processing data (global analysis, observational data, etc)
3. Parallel image and data post-processing for web posting

The fault tolerant script ensures that the operation will adjust and continue even in the face of an error or will report that there is a process ending error. The script has been written to be smart enough to retrieve the latest pre-processing data if it is not already present on the system; this ensures that the simulation will have the most recent data and/or avoid downloading data that is already present. Parallel image and data processing (through the use of child processes) has been shown to achieve a nearly linear speedup relative to the number of processors used. For example, we can easily cut the image production time in half on a single node (to produce the above images takes approximately 50 minutes on a single processor, so utilizing two processors takes approximately 25 minutes). This type of parallelism allows the capability of plotting more fields without significantly increasing the total image processing time.

5. WEB OUTPUT

Now that the above processes have created images, they must be made available for the telescope operators [9,10]. This is accomplished by posting to the MHPCC web page, http://weather.mhpcc.edu. This title page (Figure 5) gives the user the option of what model, domain, and resolution they would like to examine.
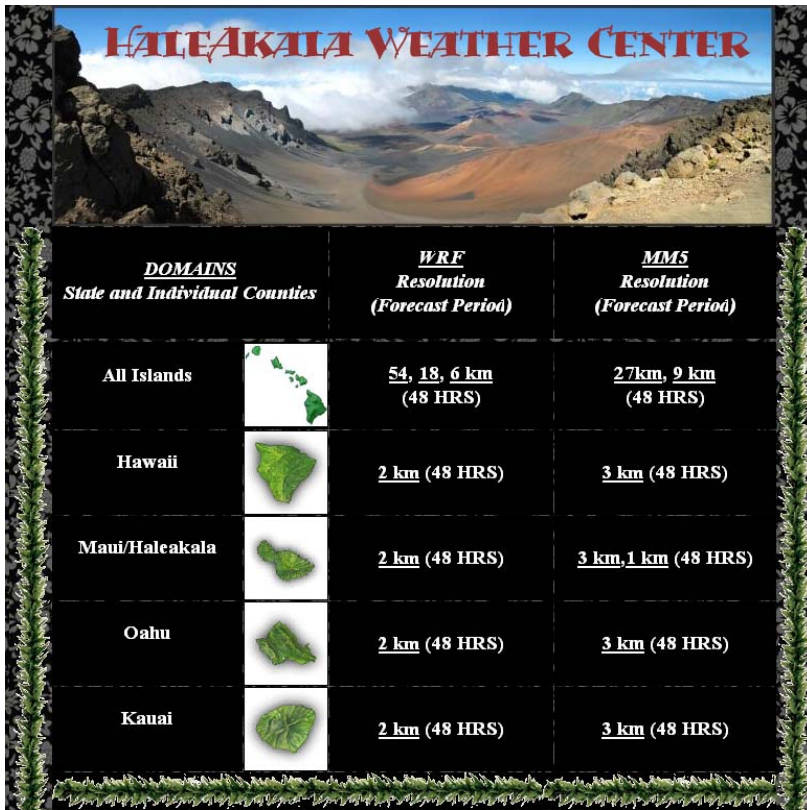
Figure 5: Top Level of Haleakala Weather Center Web Pages

From the title page, the user can select WRF or MM5 forecasts. WRF includes an all island forecast at resolutions of 54, 18, and 6 km as well as 2 km resolutions for all 4 counties (Hawaii, Maui, Oahu, and Kauai). MM5 is similar with the all island forecasts at a 27 or 9 km resolution, the 4 counties at a 3 km resolution, and the summit of Haleakala at a 1 km resolution. Once one of the above has been selected, the user is transported to a web page that initially includes an image of the wind in the selected area (Figure 6). In additional to the Hawaiian WRF and MM5 Forecasts available, there are links on the title page to national weather sources, such as the USDA Forest Service and the National Oceanic and Atmospheric Administration (NOAA). Hawaiian weather related links, such as the University of Hawaii's School of Ocean & Earth Science & Technology (SOEST), are also present.
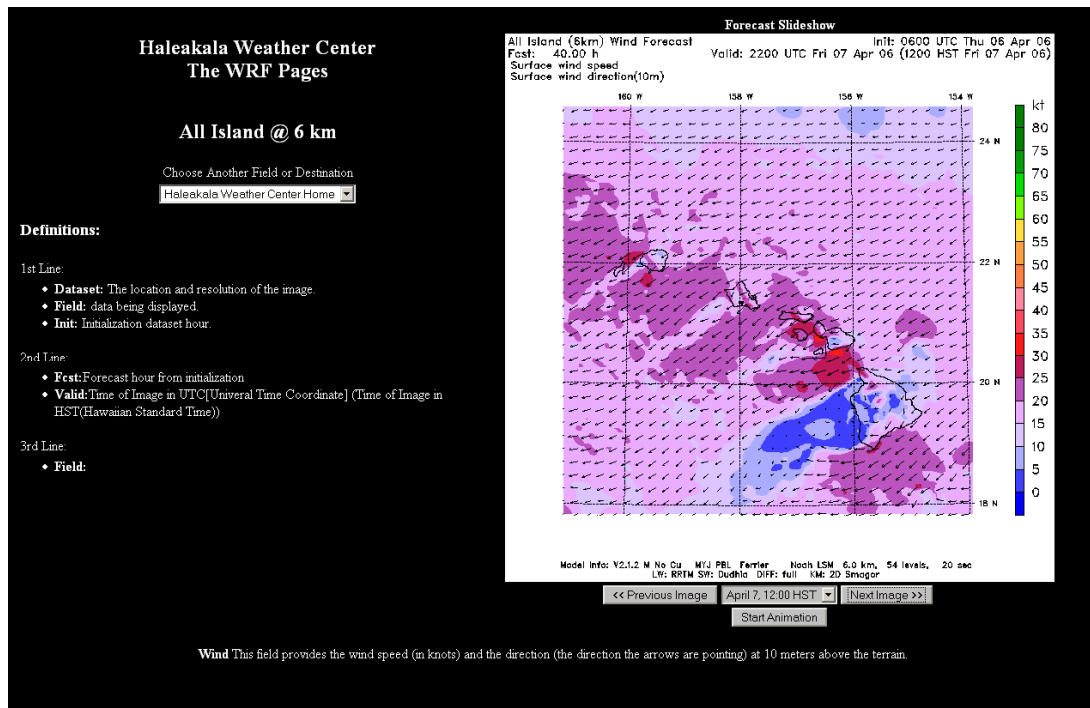

Figure 6: Regional WRF Forecast – All Island (6 km) Surface Wind (knots)
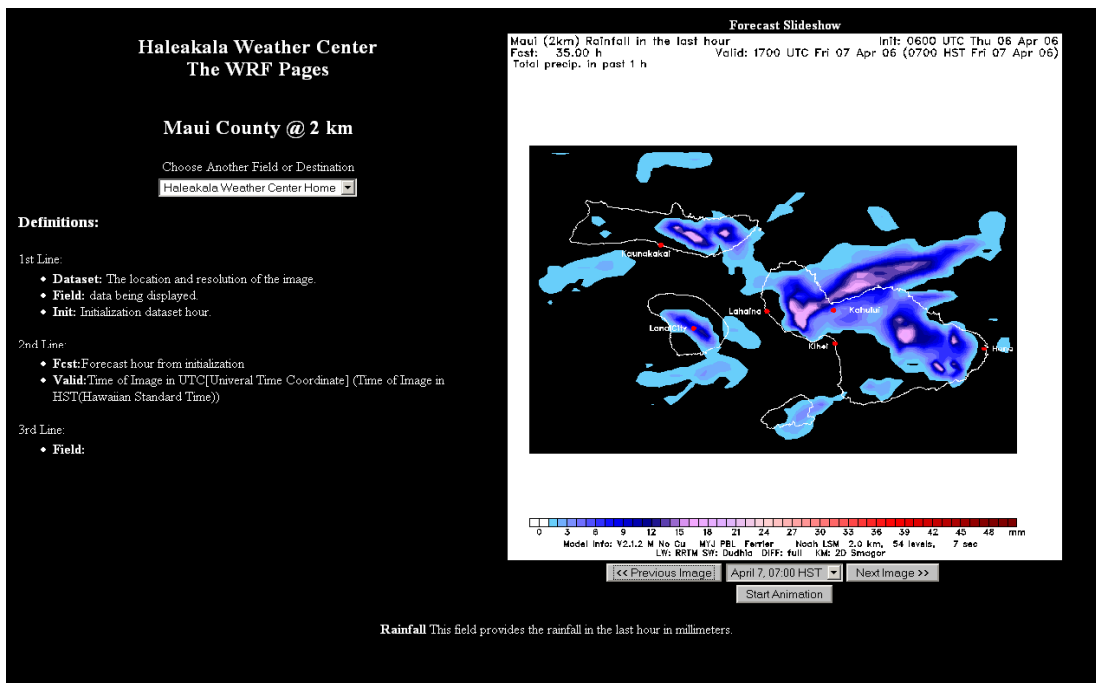
Figure 7: Regional WRF Forecast – Maui County (2 km) Rainfall in the last hour (mm)

On the regional web pages (see Figures 6 and 7), the viewer can select to see the previous or next image, through the use of small JavaScript. If the viewer prefers, an animation of the images (in 1 hour increments) can be started and stopped. Finally, the user can select any of the hourly images from a pull down menu. If the viewer would like to change the field being examined, a pull down menu on the left side of the page will transport the user to go the main menu, choose a different field, choose a different domain, or a different domain from a different model.

6. VALIDATION

Validation for Hawaiian WRF simulation comes from a variety of sources. One source is the CAPS weather sensor output from Haleakala (http://banana.ifa.hawaii.edu/caps/CAPSdata.html). These 10 sensors allow the comparison of the results of WRF predictions against an actual measurement. Another source is the sensors owned by the Hawaiian Commercial & Sugar (HC&S) Company. Also, NOAA's National Buoy Center (http://www.ndbc.noaa.gov/Maps/Hawaii.shtml) also has observational data available that includes wind speed and direction and temperature.

Techniques for actually validating the results may be more difficult and require statistics [11]. One can simply do a simple comparison of the sensor data to the model output at the corresponding time period. However, there are some difficulties that make validation of the model's predictions difficult. First, the model outputs on the hour (although this is configurable down to the minute but becomes impractical to do this for a 48-hour simulation) so that would need to be matched up to the sensor output only for the top of the hour. This is not a major obstacle, but it would be better to compare the output on a smaller time scale that matched the output of the sensors. Secondly, the sensors are usually less than 20 feet above the ground; the model's predictions can be 300 feet above the terrain. This altitude difference can adversely affect the accuracy of any comparison. Lastly and most importantly, a storm appears earlier or later than the time frame the model predicted. Hence the model has predicted an event (storm, cloud cover, rain, high winds, etc.) sooner (or later) than it actually occurs. The model has still predicted the event, just not at the exact moment that it occurred. This makes validation very difficult.

To make the best attempt at validation, one needs to look at trends in the actual weather and how well the model predicts them. If the model predicts high winds from 1-3 P.M. and the high wind actually occur from 3-5 P.M. then model still has predicted the storm within a 2-hour margin of error. In addition, another method for validation can be to match up the sensor output for these events and compare to the model's predictions. If the model predicted 40 M.P.H. winds (average speed) during the event (from 1-3

P.M.) and the actual high wind were in the neighborhood of 40 M.P.H. (average speed) during the actual event then this is an acceptable validation.

The model has been able to capture all major storm systems that have entered the state of Hawaii during its operation. Smaller, more localized events are usually captured; however, the model may predict them to be slightly less/more powerful than in reality. Commonly known events such as the trade wind inversion, diurnal weather patterns, orographic rainfall, and Kona (leeward) storms are also well predicted.

7. SCHEDULING & BENCHMARK

In order to produce daily operational forecasts, a strict schedule must be maintained and a choice must be made as to how many processors will be utilized for the model's execution. In order to determine this, a benchmark was done to determine the total processing time and the parallel efficiency. Processing time was examined so that we may maintain the schedule describe in Section 4. The goal of having prediction ready before 8 AM (i.e. less than 6 hours of WRF execution time) would be helpful to operators to determine a schedule for the current and following evening. Speedup and parallel efficiency were examined to determine the most cost effective choice. In addition, the efficiency will be compared to the benefit of the total processing time for the model's completion. The benchmark for the daily Hawaiian Islands simulation can be seen in Table 1.

The choice of 16 processors or less can be dismissed, because it prevents the run from being completed in our goal of under 6 hours. Although the 32-processor parallel efficiency of 42% is acceptable and it allows us to complete the model run with our goal, it may insufficient for completion of our future work (specifically run for 72 simulation hours instead of just 48). 64-processors is acceptable even though its parallel efficiency is only 32% since we have access to this many processors and the drop in execution time may permit the extra cost associate with extending the forecast to 72 hours (would be ~5.7 hours which is almost exactly the same as the acceptable time of 32-processor run for 48 hours). If more processors were used, the model run would complete faster, but at a higher price. Since the goal is met with 32 or 64 processors, there is no need to use more processors.

Processors	Time (Avg) (Seconds)	Time (Avg) (H:M)	Speedup	Parallel Efficiency
1	276696	76:52	1.00	1.00
2	144180	40:03	1.92	0.96
4	88668	24:38	3.12	0.78
8	52164	14:30	5.30	0.66
16	34452	9:34	8.03	0.50
32	20628	5:44	13.41	0.42
64	13716	3:49	20.17	0.32
128	11317	3:06	24.45	0.19

Table 1: WRF Benchmark for the Hawaiian Islands Simulation

8. FUTURE WORK

There is additional work that can be done to improve the model's predictive capabilities. Some will help the reliability of the model in producing a forecast in the required time frame; others will help the accuracy of the model. A list of future work includes:

1. Porting the code to another machine. Having a secondary machine available when the primary machine is unavailable (whether it be due to maintenance or higher priority users) will ensure no breaks in daily operational service.
2. Observation data inclusion. Currently no observational data is included in the daily predictions; it is only used for validation purposes.
3. Inclusion of ≤ 100-meter terrain data. Currently the model uses 30-second (~0.9 km) terrain data, which limits model from running with accurate terrain data at sub-kilometer resolutions.
4. Increase horizontal resolution of Hawaiian counties from 2 kilometer to sub-kilometer. This is dependent on inclusion of ≤ 100-meter terrain data. In addition, more research must be done to investigate the accuracy of model at this resolution. It is not entirely clear how the model will behave at a finer resolution and hence the physics packages used by the model may need to be improved and/or modified.
5. Extend the forecast from 48 to 72 simulation hours. Validation of additional simulation hours.
6. Provide the seeing or optical turbulence product with the current forecasts. Significant work has already been done with optical turbulence modelers using the MM5 and WRF models using both the Dewan and Jackson Models [12]. The next stage is to actually test the current WRF model runs with observational data (i.e. radiosondes) to see how accurate the model can actually perform.

9. SUMMARY

A methodology has been created that will produce fine resolution weather forecasts for the state of Hawaii utilizing the next generation WRF model. This methodology is focused on providing the required forecasts in a minimal time as to still be useful to everyone from the general public to scientist at Haleakala using it to determine if the weather predictions are within their operational limits. The web output has been chosen to given telescope operators the necessary fields needed to make decisions regarding whether or not the weather conditions will allow the utilization of the telescopes on Haleakala. This will allow better scheduling and improve the potential efficiency of telescope operations.

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