Applications of Four Dimensional Analysis to Examine Intensity Variations of Hurricane Lili using Aqua, Terra, and other Satellite Data

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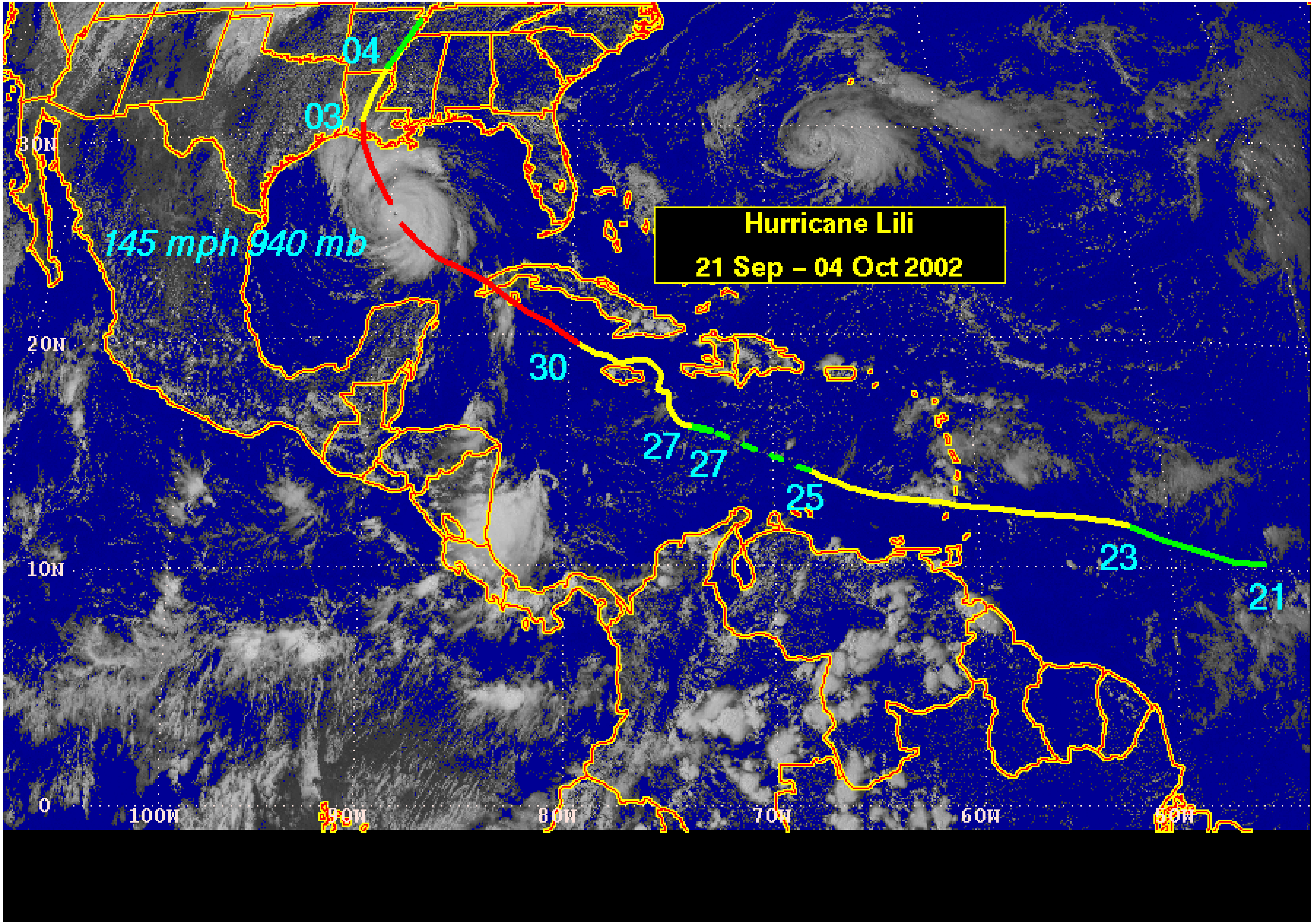
I. Background on Hurricane Lili (2002)
II. Datasets and assimilation strategies
III. MM5 4DVAR work
IV. SST gridded data generation from satellite and buoy
V. Summary
VI. Commercial potential

I. Background on Hurricane Lili (2002)

HURRICANE LILI: A GOOD EXAMPLE OF THE LIMITATIONS OF OPERATIONAL INTENSITY FORECASTING



HURRICANE LILI DISCUSSION NUMBER 46
NATIONAL WEATHER SERVICE MIAMI FL
5 PM EDT WED OCT 02 2002

LILI WENT THROUGH ANOTHER BURST OF INTENSIFICATION THIS AFTERNOON... WITH THE CENTRAL PRESSURE FALLING FROM 954 MB TO 941 MB IN ABOUT 5 HR. THE HURRICANE HAS CONTINUED TO DEEPEN AT A SLOWER RATE SINCE 16Z...WITH THE CENTRAL PRESSURE FALLING TO 938 MB AT 20Z. THE MAXIMUM FLIGHT LEVEL WINDS FOUND BY THE VARIOUS AIRCRAFT SAMPLING LILI SO FAR ARE 136 KT...SO THE INITIAL INTENSITY IS SET TO 120 KT. LILI IS SHOWING SIGNS OF PEAKING...AS THE AIRCRAFT AND SATELLITE IMAGERY INDICATE THE BEGINNING OF AN OUTER EYEWALL THAT WILL LIKELY BRING A HALT TO THE CURRENT INTENSIFICATION.
(TEXT DELETED)

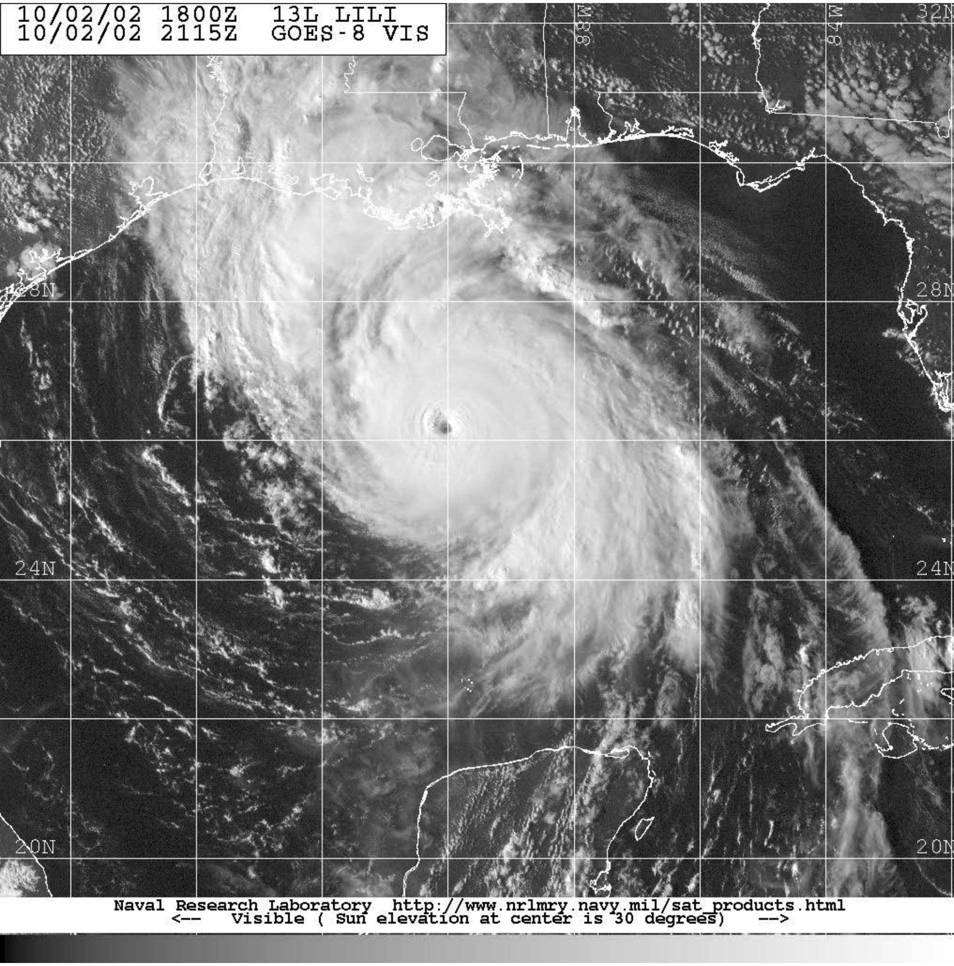
IN ADDITION TO THE CONCENTRIC EYEWALLS...THE ACTUAL INTENSITY IS CATCHING UP WITH THE SATELLITE SIGNATURE AND THE OUTFLOW IS BEING RESTRICTED TO THE WEST AND SOUTHWEST BY AN UPPER-LEVEL TROUGH. THESE THINGS SUGGEST THAT LILI SHOULD PEAK IN THE NEXT 6-12 HR THEN UNDERGO FLUCTUATIONS IN STRENGTH UNTIL LANDFALL. REGARDLESS OF THE EXACT INTENSITY...LILI SHOULD MAKE LANDFALL AS A MAJOR HURRICANE.

FORECASTER BEVEN

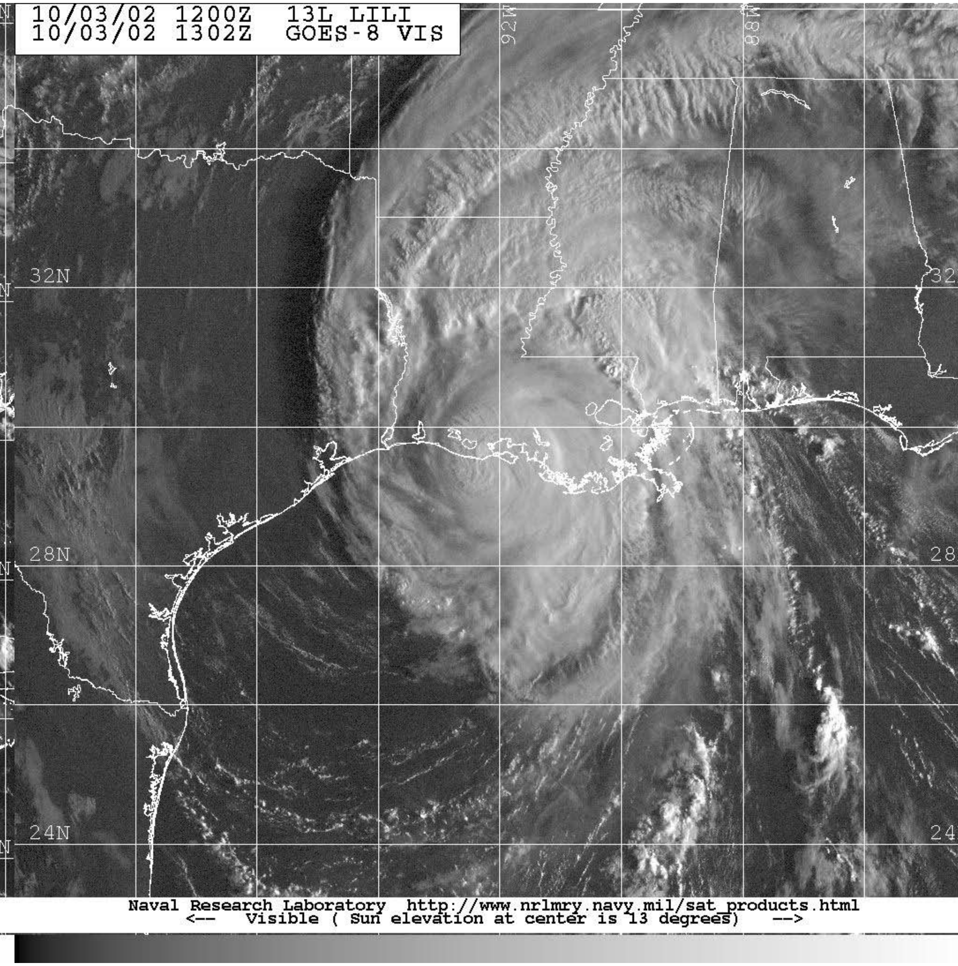
FORECAST POSITIONS AND MAX WINDS

INITIAL	02/2100Z	25.9N	90.0W	120 KTS
12HR VT	03/0600Z	27.5N	91.4W	125 KTS
24HR VT	03/1800Z	29.8N	92.3W	125 KTS...INLAND
36HR VT	04/0600Z	32.2N	91.9W	65 KTS...INLAND
48HR VT	04/1800Z	36.1N	89.0W	35 KTS...INLAND EXTRATROPICAL
72HR VT	05/1800Z	45.0N	74.0W	30 KTS...INLAND EXTRATROPICAL

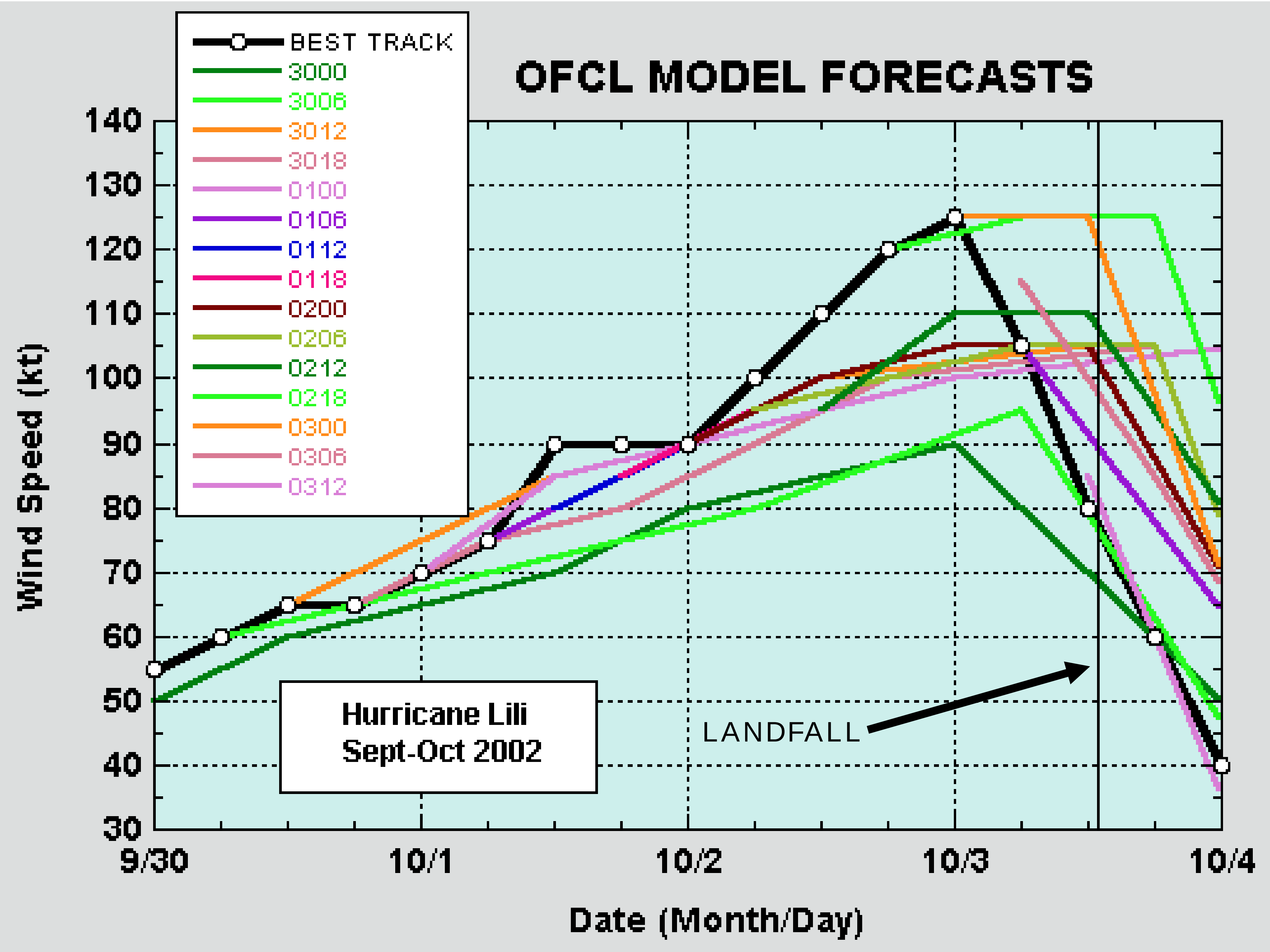
AFTER QUICKLY STRENGTHENING TO A STRONG CAT. 4 HURRICANE, LILI WEAKENED EVEN MORE RAPIDLY THAN IT HAD INTENSIFIED



LILI NEAR ITS MAXIMUM INTENSITY OF 145 MPH



LILI MAKING LANDFALL AS A CAT. 1 HURRICANE



OFCL MODEL FORECASTS
BEST TRACK
3000
3006
3012
3018
0100
0106
0112
0118
0200
0206
0212
0218
0300
0306
0312
Wind Speed (kt)
140
130
120
110
100
90
80
70
60
50
40
30
9/30
10/1
10/2
10/3
10/4
Date (Month/Day)
Hurricane Lili
Sept-Oct 2002
LANDFALL

LILI'S RAPID WEAKENING JUST BEFORE LANDFALL IS NOT WELL UNDERSTOOD.

WAS IT CAUSED BY:

- AN INTERNAL (INNER CORE, E.G. EYEWALL) MECHANISM?

- VERTICAL WIND SHEAR, OR OTHER ENVIRONMENTAL INFLUENCES SUCH AS MOISTURE, STABILITY?

OR

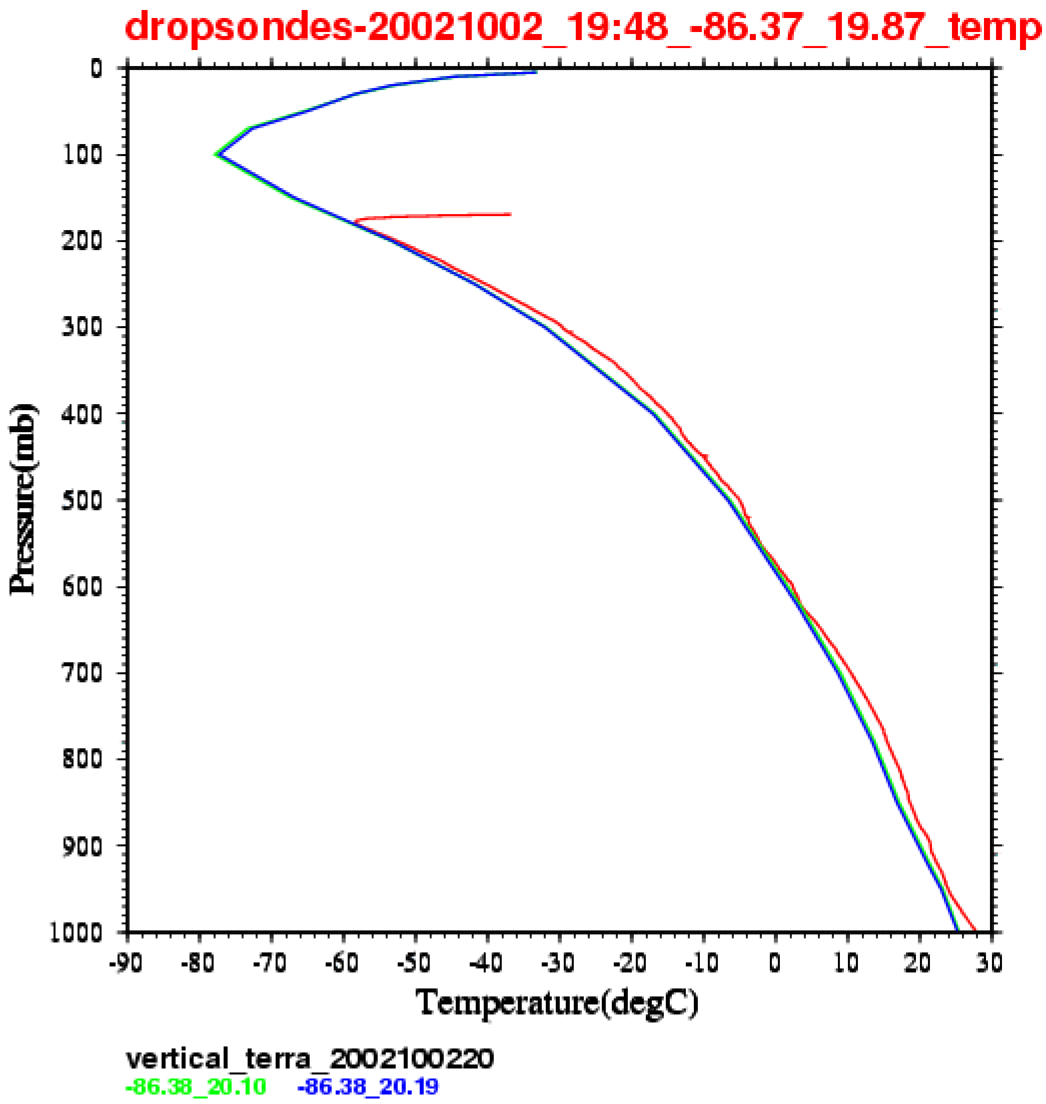
-THE OCEAN, SUCH AS ISIDORE'S WAKE AND/OR COOLER SHELF WATERS?

By analyzing conventional, NASA/NOAA satellite, and reconnaissance data, and assimilating in a mesoscale model for sensitivity runs, we are testing these hypotheses.

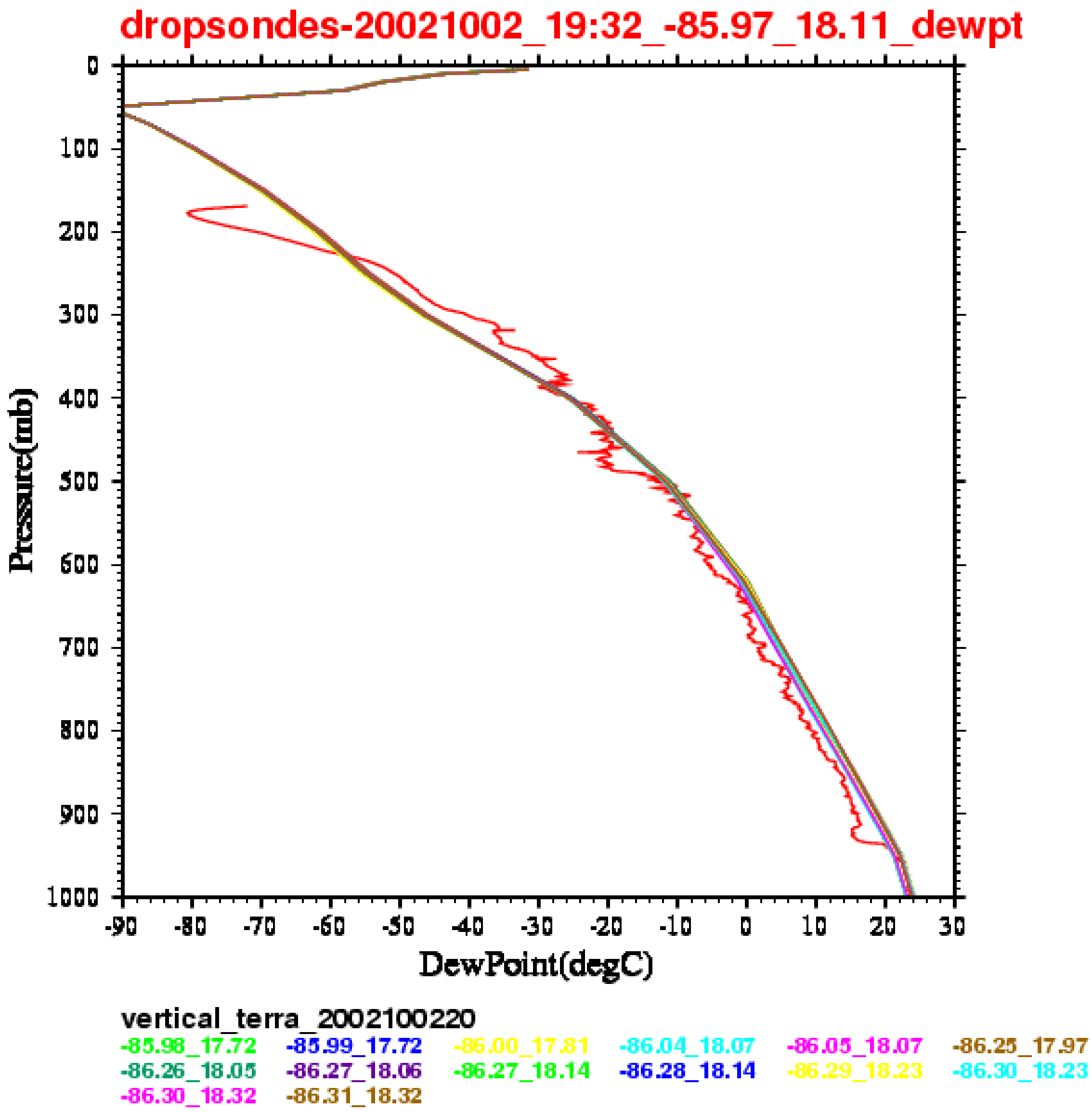
We are also analyzing Lili's rapid intensification on 10/2/02, which also was not predicted accurately.

II. Datasets and assimilation strategies

- Conventional (Radiosonde, METAR, buoy, ships)
- AVN model data for boundary conditions
- Satellite:
  - SST: Terra, Aqua, TRMM, AVHRR
  - T, Td profiles: Terra
  - Surface wind: QUIKSCAT
  - Cloud-drift winds: GOES
- Reconnaissance data (T, Td profiles)

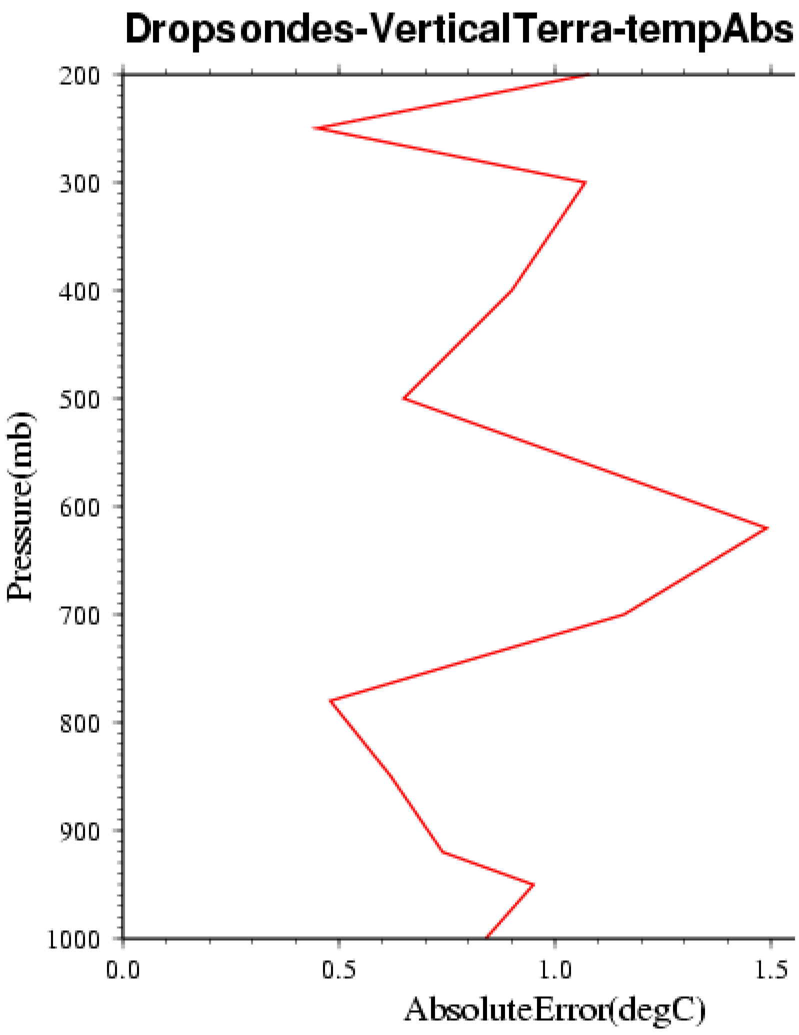


Terra temperature profile appears accurate

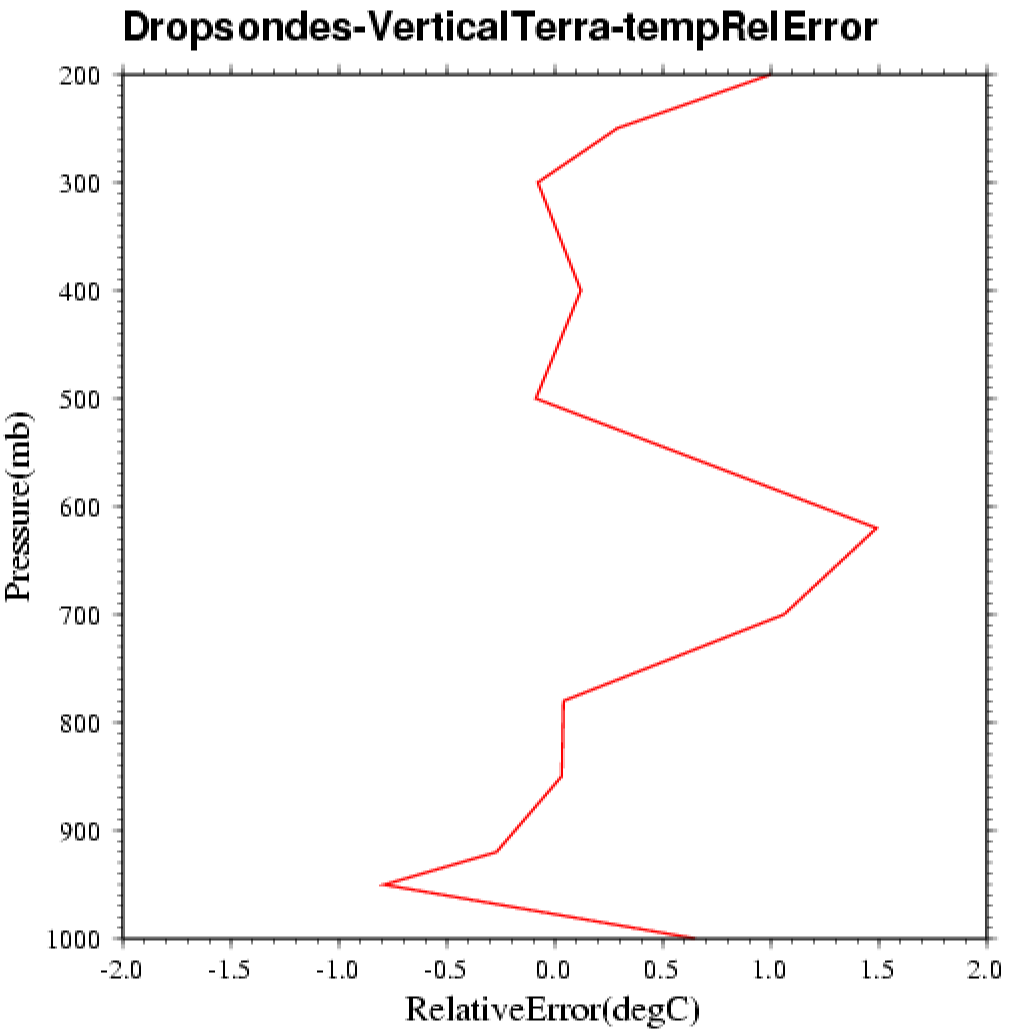


Terra dewpoint less accurate, missed small features, but usable

Absolute error



Bias



What is data assimilation?

Data assimilation is the technique whereby observational data are combined with output from a numerical model to produce an optimal estimate of the evolving state of the system.

DARC

In variational data analysis the analysis is found by minimisation of a cost function,

$$J_{3DVar} = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b)+\frac{1}{2}(H(\mathbf{x})-\mathbf{y})^T\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y}) \tag{1}$$

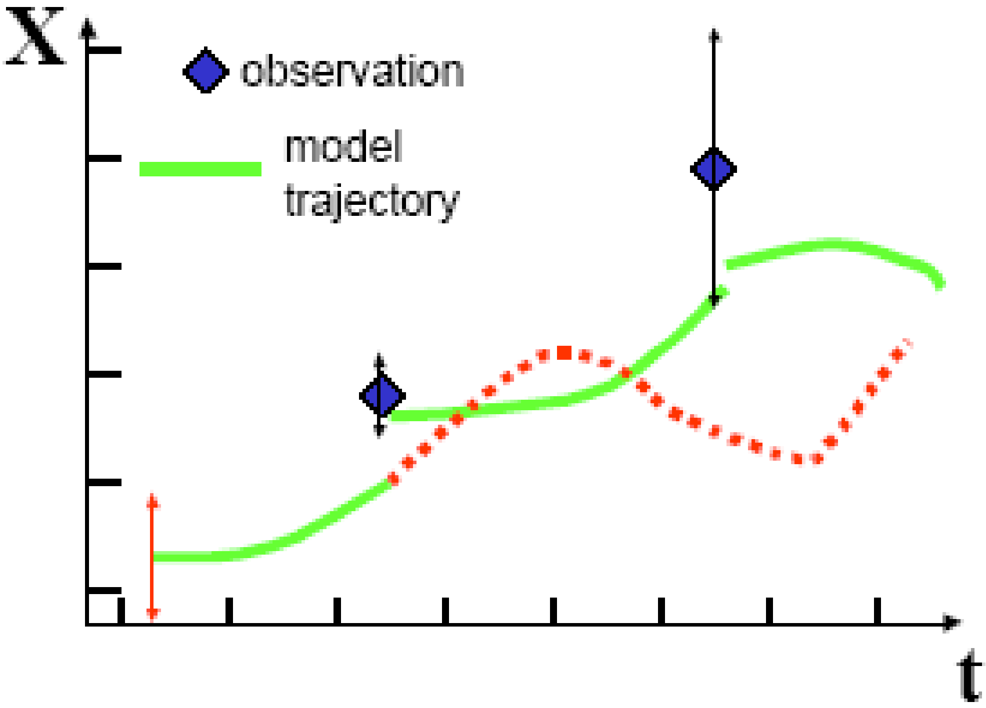
$$J_{4DVar} = \frac{1}{2}(\mathbf{x}_0-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}_0-\mathbf{x}_b)+\frac{1}{2}(H(M_i(\mathbf{x}_0))-\mathbf{y}_i)^T\mathbf{R}^{-1}(H(M_i(\mathbf{x}_0))-\mathbf{y}_i) \tag{2}$$

with respect to the state vector $\mathbf{x}$. Here $\mathbf{y}$ is a vector containing all observations, while H is a so-called *observation operator*, which maps from model space to observation space (examples will be given later). $\mathbf{x}_b$ is the background (a recent NWP forecast, valid at the time of the data analysis). $\mathbf{B}$ is the error covariance matrix of the background field, $\mathbf{R}$ is the error covariance matrix of the observations. The matrices are of order $N^2_{NWP-variables}$ and N^2_{obs}, approximately 10^{14} and 10^8 for a typical NWP run at DMI.

In 3DVar one operates with a single data assimilation time window centred on the time of the analysis, e.g. a 3 or 6 hour window for a NWP system making a new analysis for every 6 hours, or a 3 hour window for a 3 hour cycling system. For each observational site the system selects the datum closest in time to the analysis time, if there are other observations from the site they are rejected.

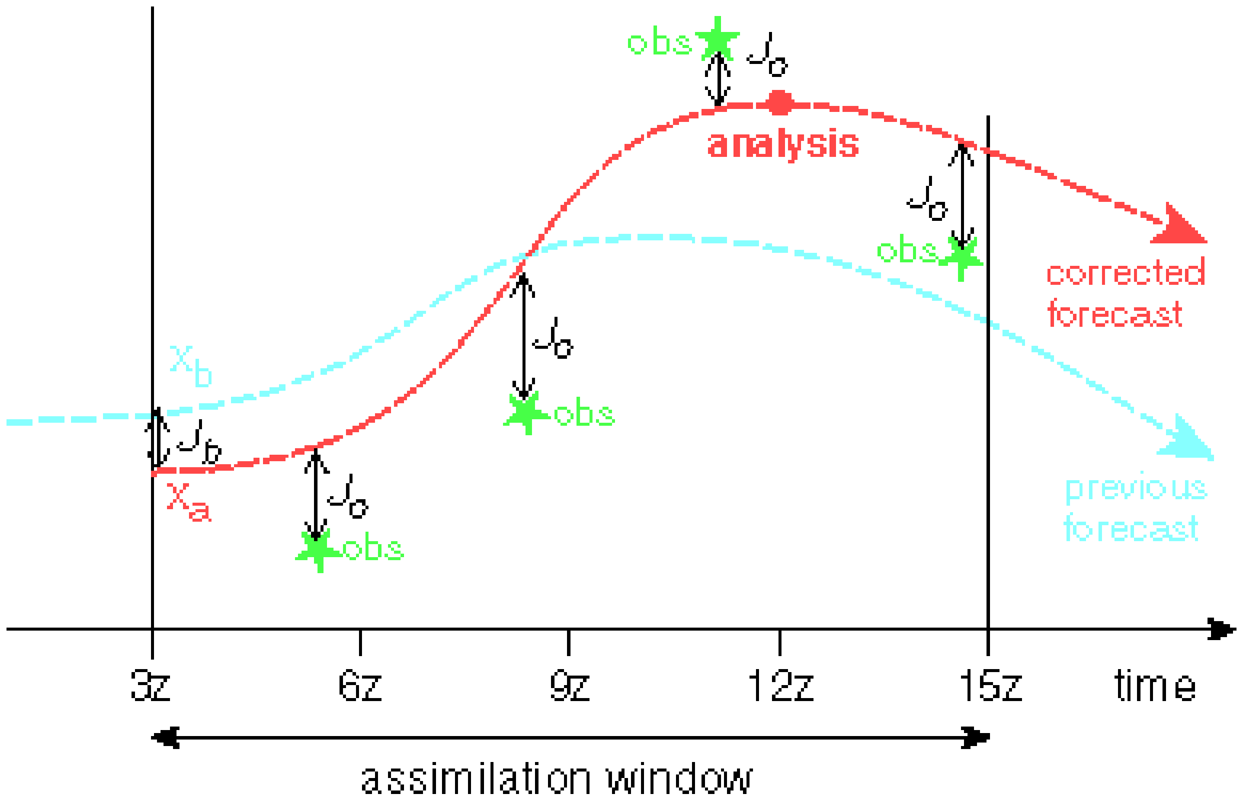
In 4DVar the observations are binned into the time-slots i, and M_i is the NWP model operator which turns state vector $\mathbf{x}_0$ into its forecast value at time i. Typical time-slots are 1 hour wide. This enables one to use observations from the same site obtained at different times, and it minimises the offset in time between the time of the observations and the valid time for the forecast fields against which the observations are compared. The drawback is that 4DVar requires far more computer-time.

3DVAR: Observation increments from different times are lumped together. A new analysis is done, and forecast is recycled.



Analogy: Drive with eyes closed: open eyes every 10 seconds and correct trajectory

4DVAR allows observation increments to be used at the times of the observations and corrects forecasts repeatedly over assimilation window, then initiates a forecast.



Computationally demanding

The systems used to quality control the observational data include

- *Bad reporting practise check.*
- *Blacklist check.* For stations which are found to 'always' report erroneous data.
- *Gross check.* Against some limits, e.g. from climatology.
- *Background check.* Based on the deviation between the observation and the expectation based on a short term forecast.
- *Buddy check.* Checking against nearby observations.
- *Redundancy check.*

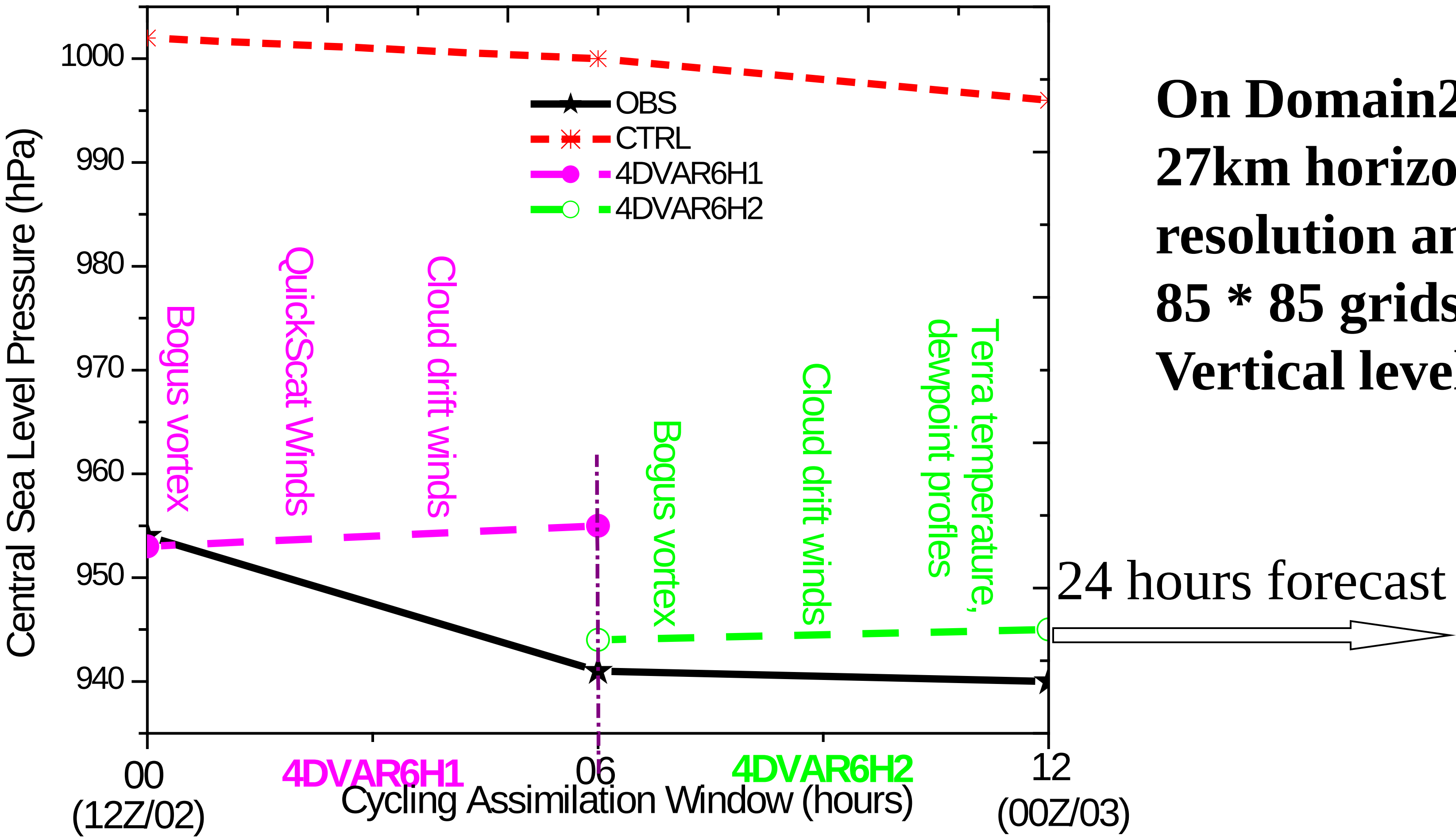
In addition observations are selected or rejected according to the time they were obtained. For a given type of observation from a given site the observations closest to the centre of the data assimilation time window is chosen. For 3DVar and most other assimilation systems (see later for definitions) this window consists of a single rather large time slot, e.g. 3 or 6 hours, while in 4DVar the window is broken down into smaller sub-windows, being typically 1 hour wide each, while the full window may be larger than in 3DVar. As a result more observations can be utilised in 4DVar.

Model computational steps:

1) Quality control
2) Hurricane vortex algorithms
3) MSU --- Cressman scheme (simpler than 3DVAR); 9-km resolution in MM5
4) NCAR --- 4DVAR; 27-km resolution in MM5
5) 6-hour cycling for both types of schemes
6) SST forcing using satellite data in progress

III. MM5 4DVAR work

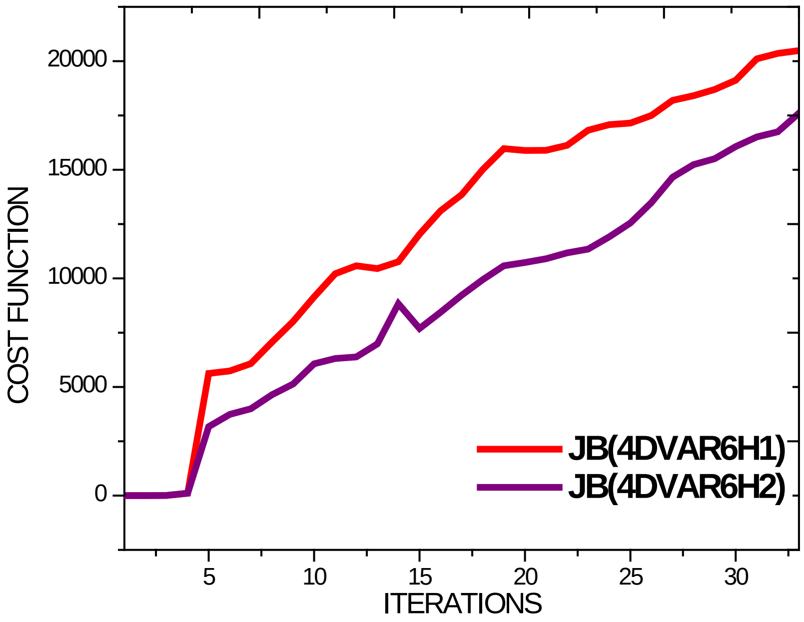
4D-Var cycling experiment design for weakening period

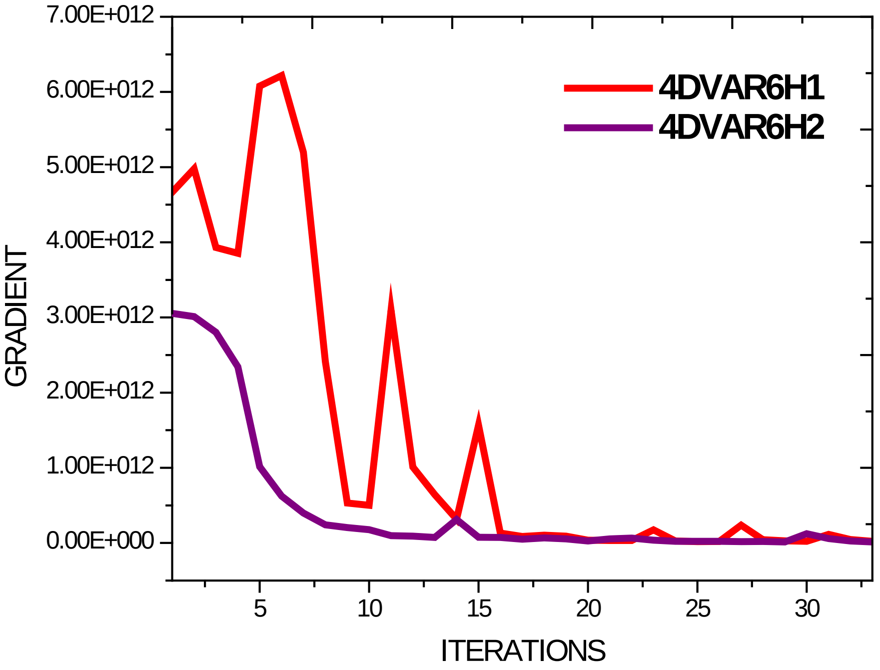


On Domain2 with 27km horizontal resolution and 85 * 85 grids. Vertical levels:33

For the intensification, we did the same experiment, on domain2 with 27km horizontal resolution and 118*142 grids and 33 layers.

Cost function and gradient in 4DVAR6H1 and 4DVAR6H2 (weakening period)

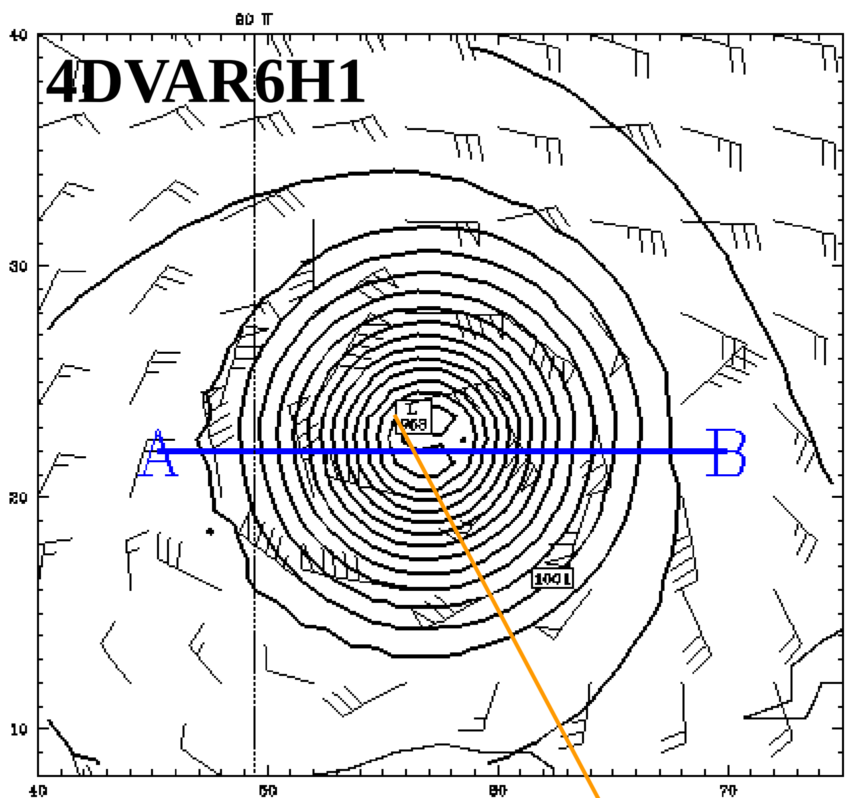


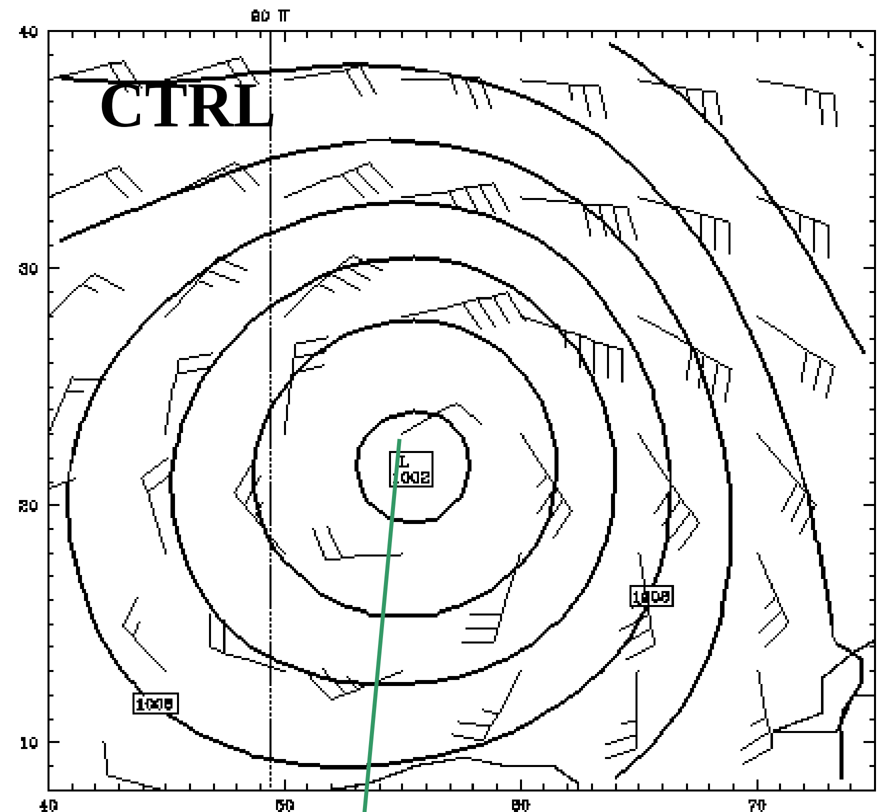


Gradient for both 4DVAR6H1 and 4DVAR6H2 have good convergence, which show all data were assimilated well.

30 iterations were integrated in each 4DVAR assimilation window. Each iteration takes about 5 hours.

Optimal initial SLP of 4DVAR6H1 at 1200 UCT 2 October





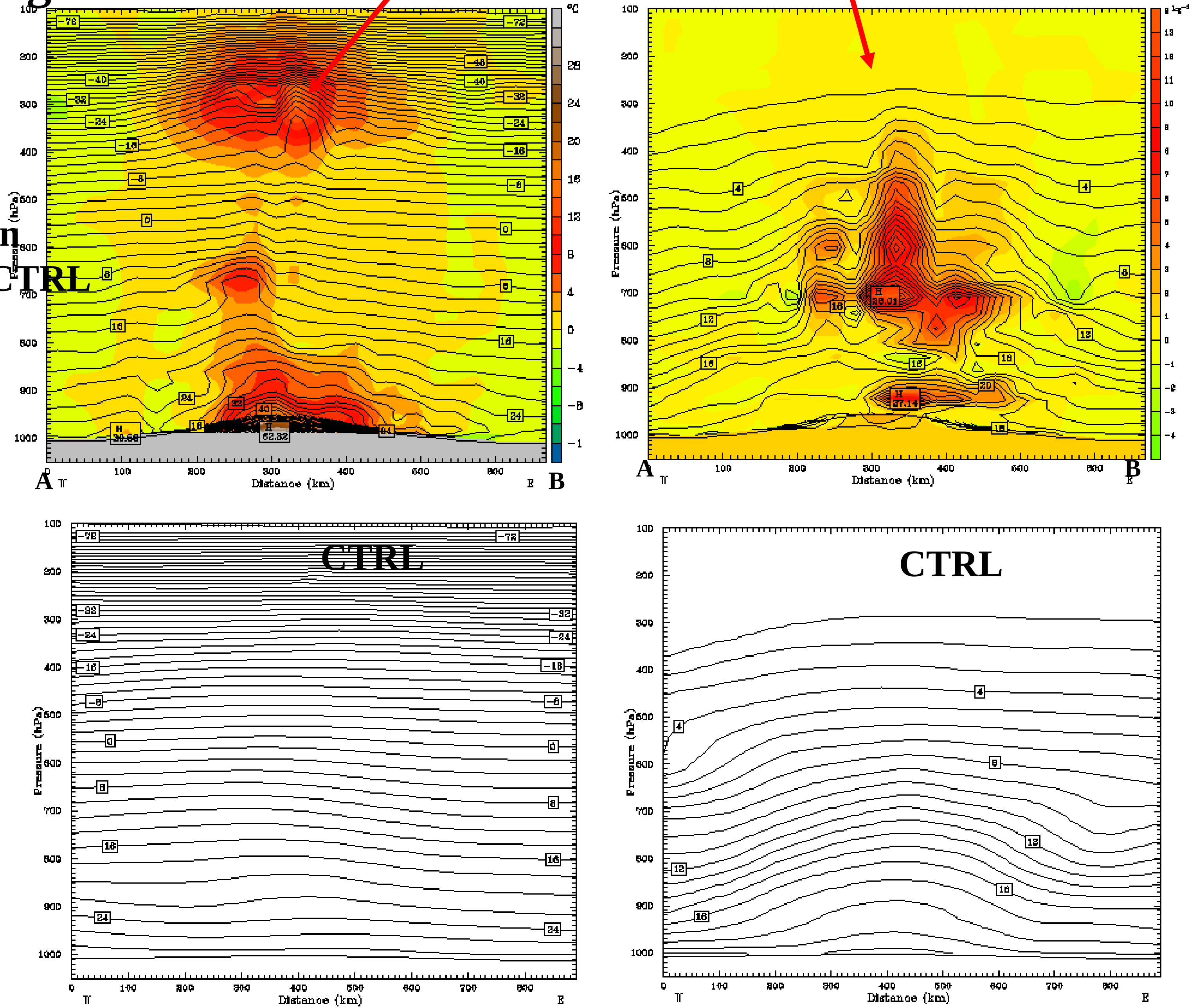
953 hPa

1002

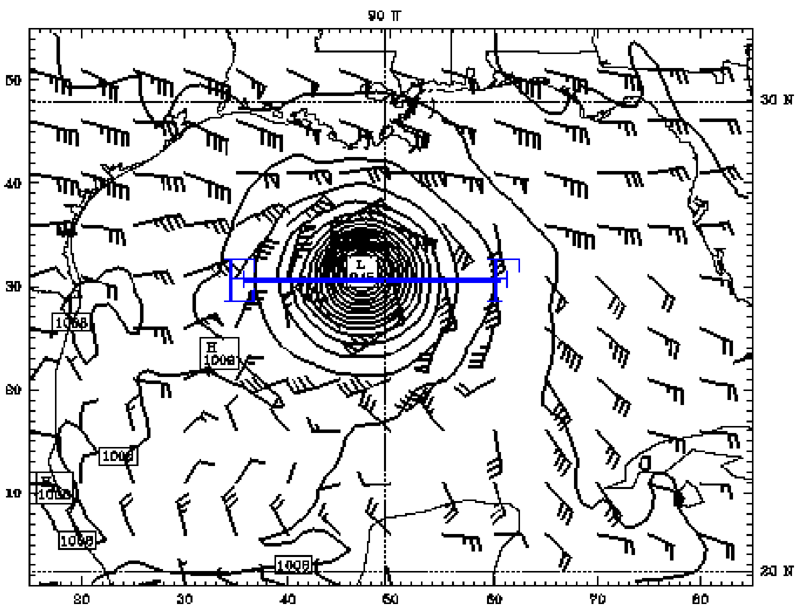
OBS=954 hPa

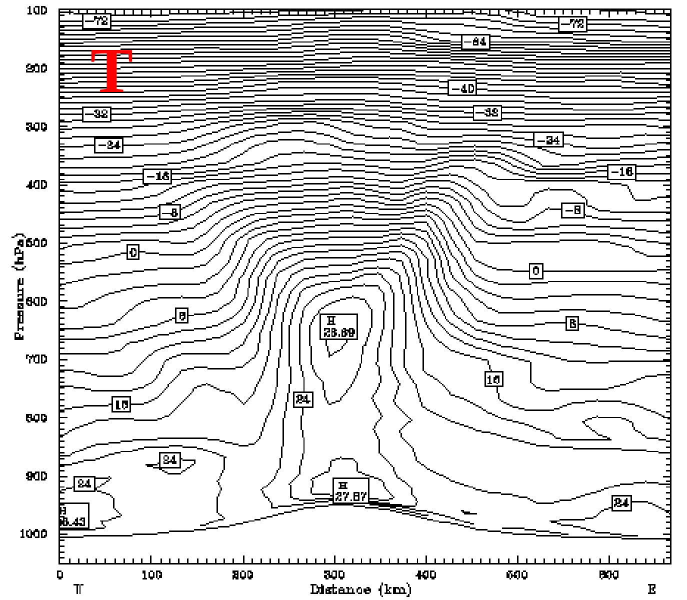
Optimal initial cross section of temperature and specific humidity (contour), along line ‘AB’

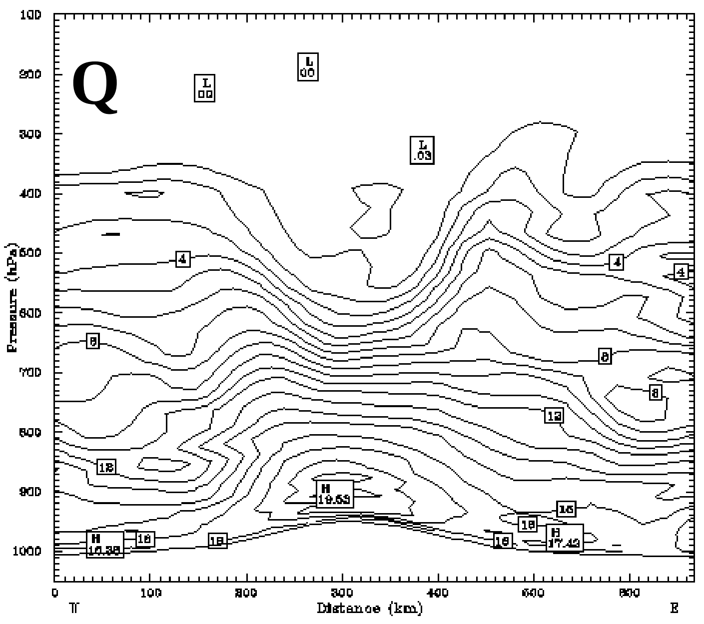
Shadow is the difference between 4DVAR6H1 and CTRL

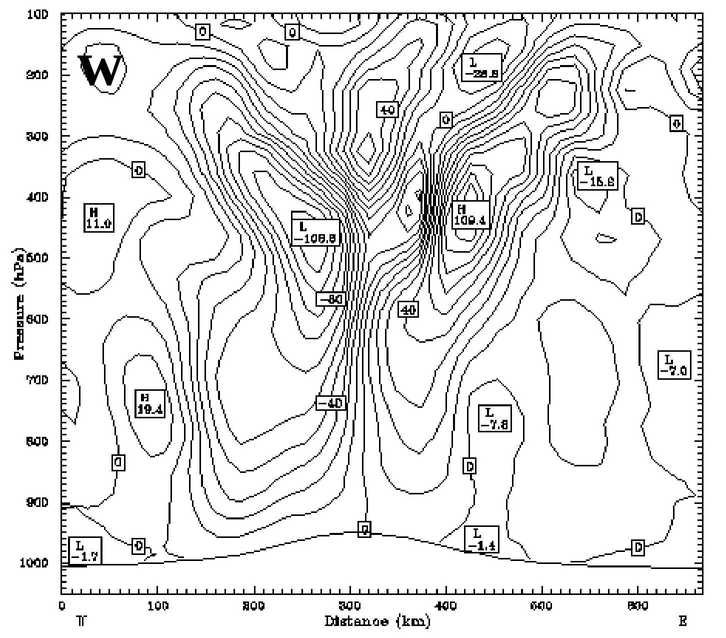


Optimal initial condition of 4DVAR6H2 at 0000 UTC 3 Oct.





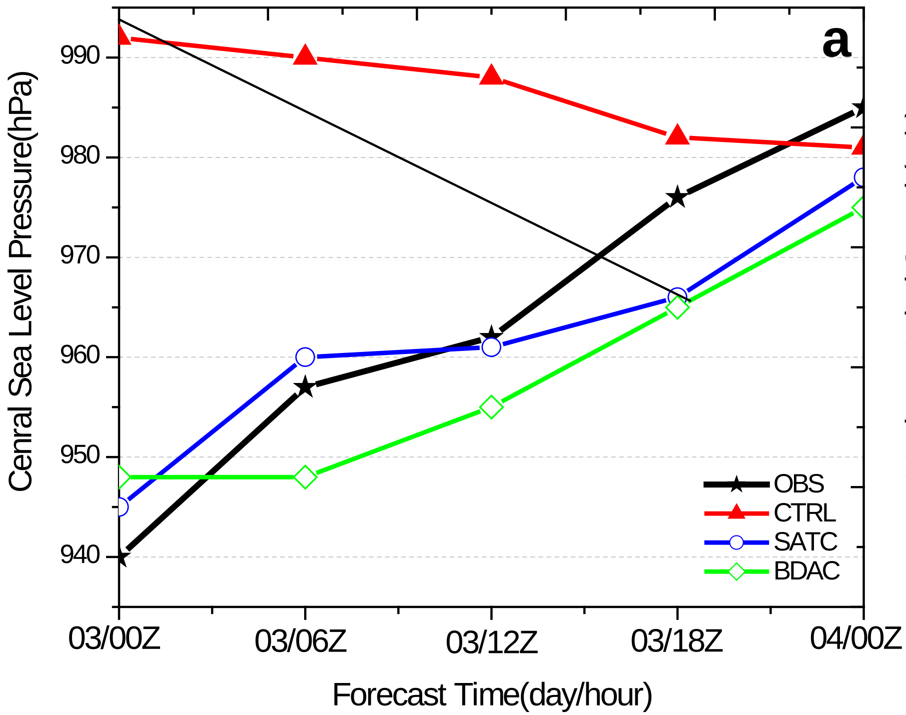


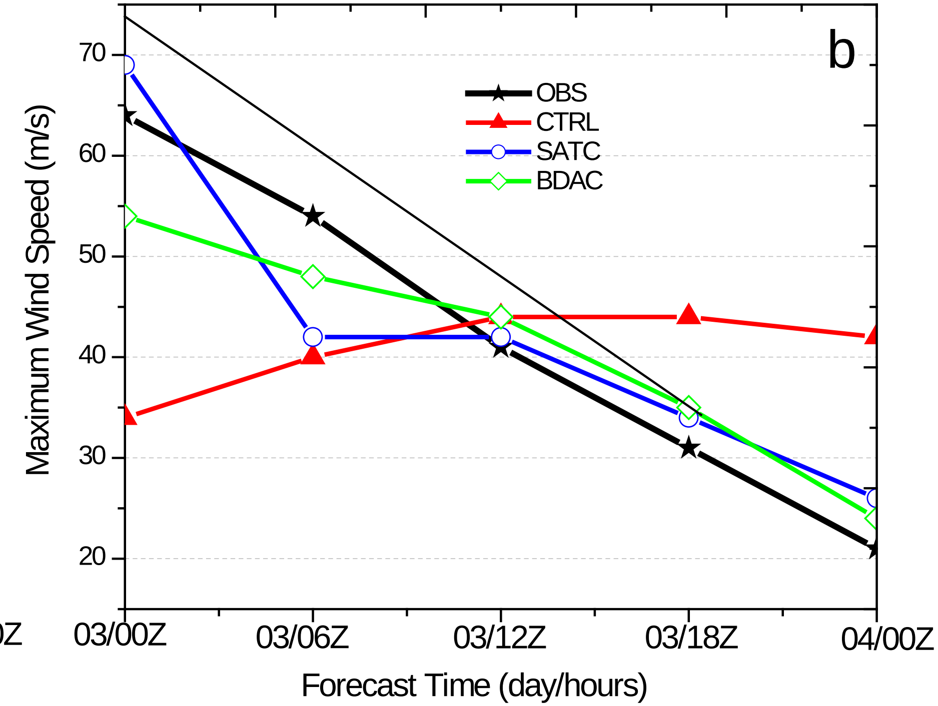


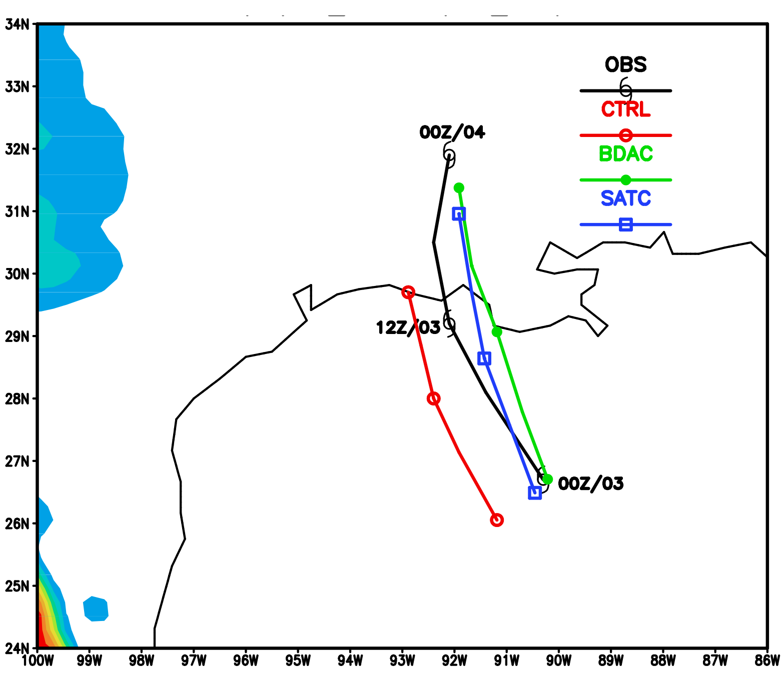
Based on the initial condition (at 0000 UTC 3 Oct.) from 4D-Var cycling experiment,
24 hour forecast is conducted on 3 nested domains.
Initial condition of domain 1st come from AVN, domain 2nd Come from this, and domain 3rd is Interpolated from domain 2nd.

The grid on 3 domain is :	**48*50,**	**85*85,**	**142*142**
Resolution:	**81,**	**27,**	**9km**
Vertical:	**33 layers**		

Forecast result analysis for weakening.

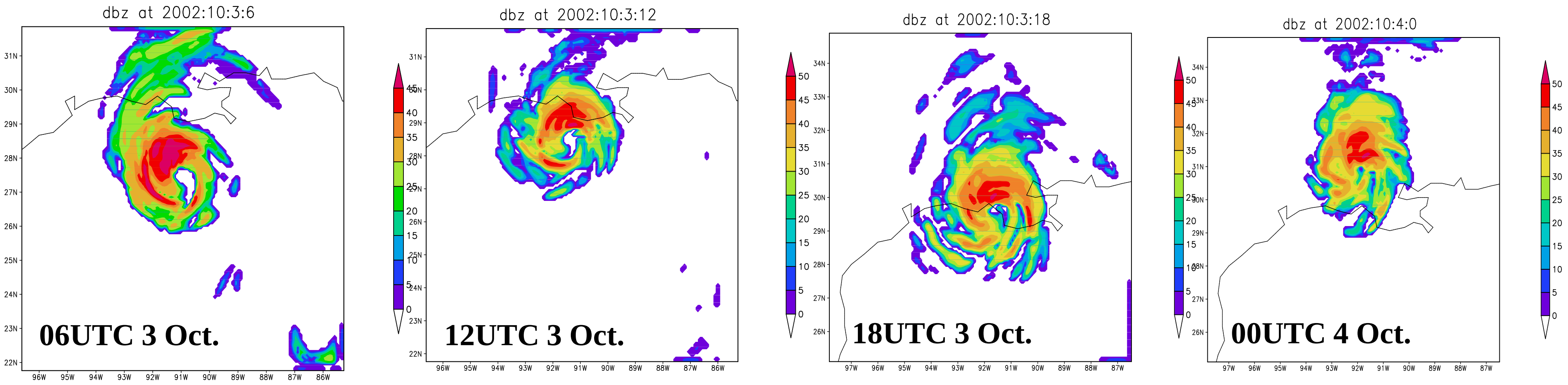




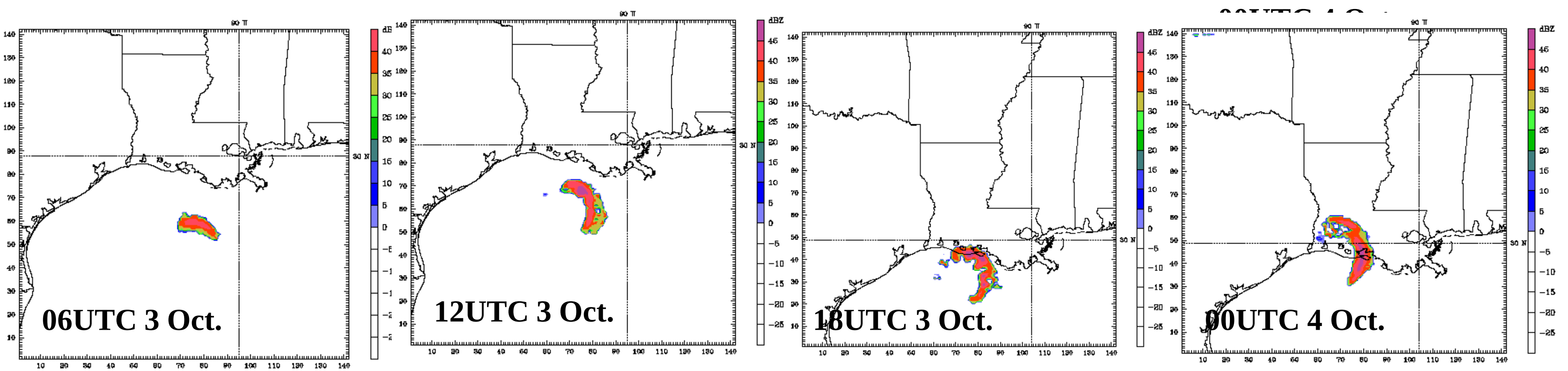


SATC: the cycling experiment including both satellite data and bogus

BDAC: the cycling experiment Only including the bogus

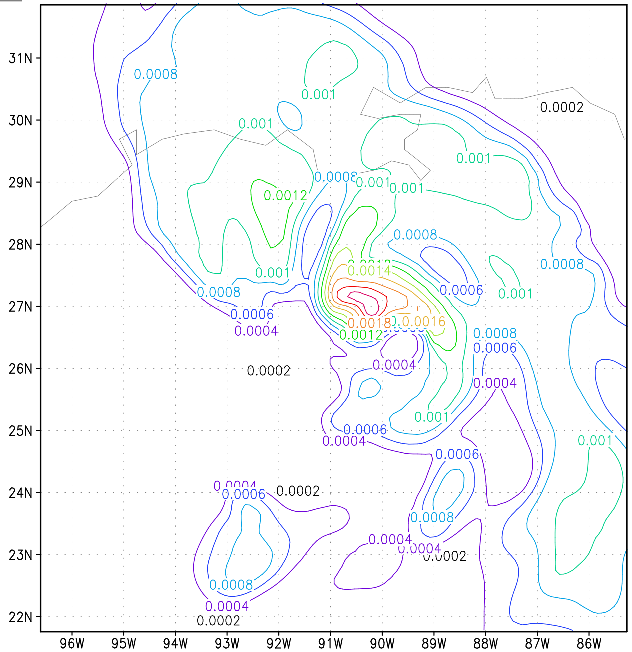


24-h Simulation of Radar reflectivity of SATC

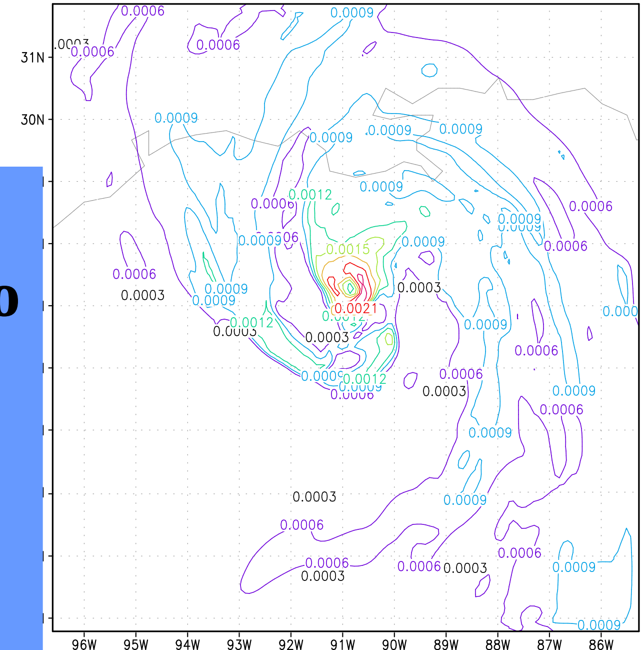


24-h Simulation of Radar reflectivity of CTRL

mixing ratio (kg/kg) on 300 hPa at 2002:10:3:0



mixing ratio (kg/kg) on 300 hPa at 2002:10:3:3

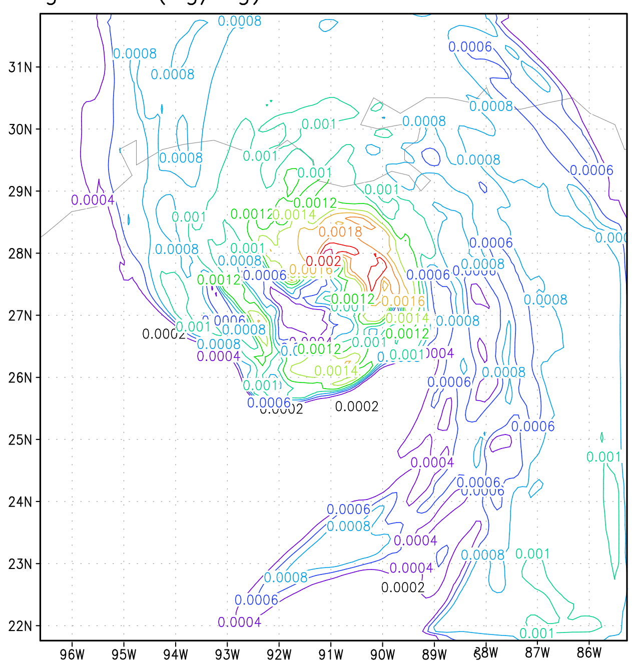


300 mb Mixing ratio

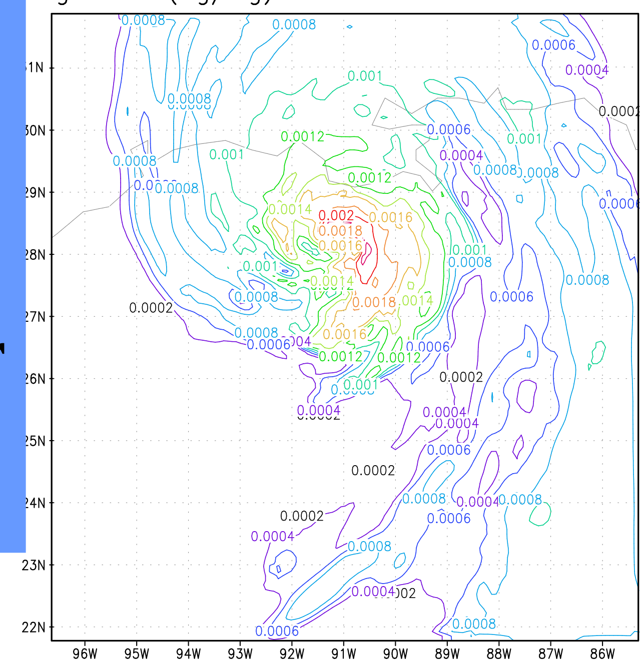
Dry air intrusion causing some weakening?

Terra and dropsonde show dry air aloft on west side

mixing ratio (kg/kg) on 300 hPa at 2002:10:



ing ratio (kg/kg) on 300 hPa at 2002:10:3:9



II. SST grid generation from satellite and buoy

SST Datasets

Satellites

Aqua and Terra – NASA EOS "Level-2" 2km data in HDF format

http://eospso.gsfc.nasa.gov and http://eosdatainfo.gsfc.nasa.gov

AVHRR - NASA JPL 4km global data in HDF format

(http://podaac.jpl.nasa.gov/sst/)

Quality Control data

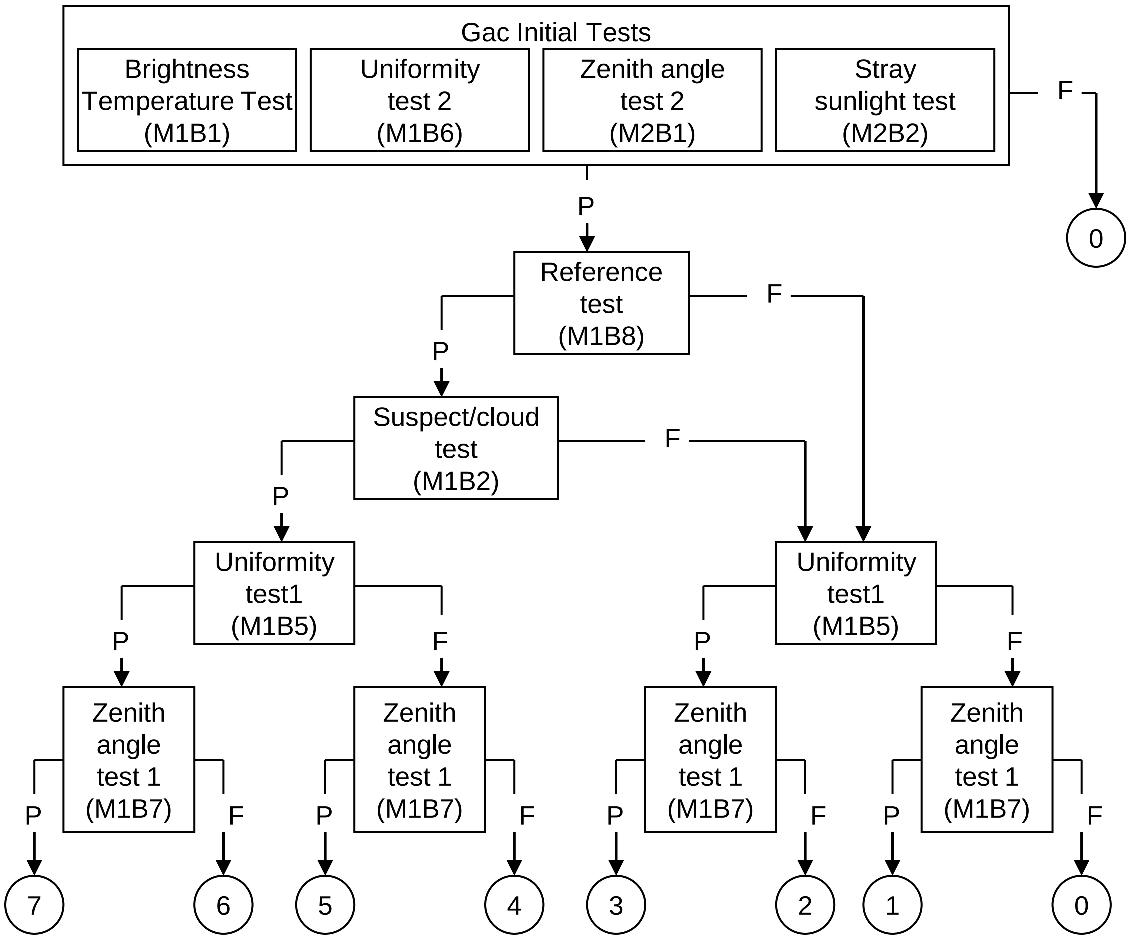
http://www.nodc.noaa.gov/sog/pathfinder4km/userguide.html

TRMM - TMI data (http://www.remss.com/tmi/tmi_description.html)

Buoys

http://www.ndbc.noaa.gov

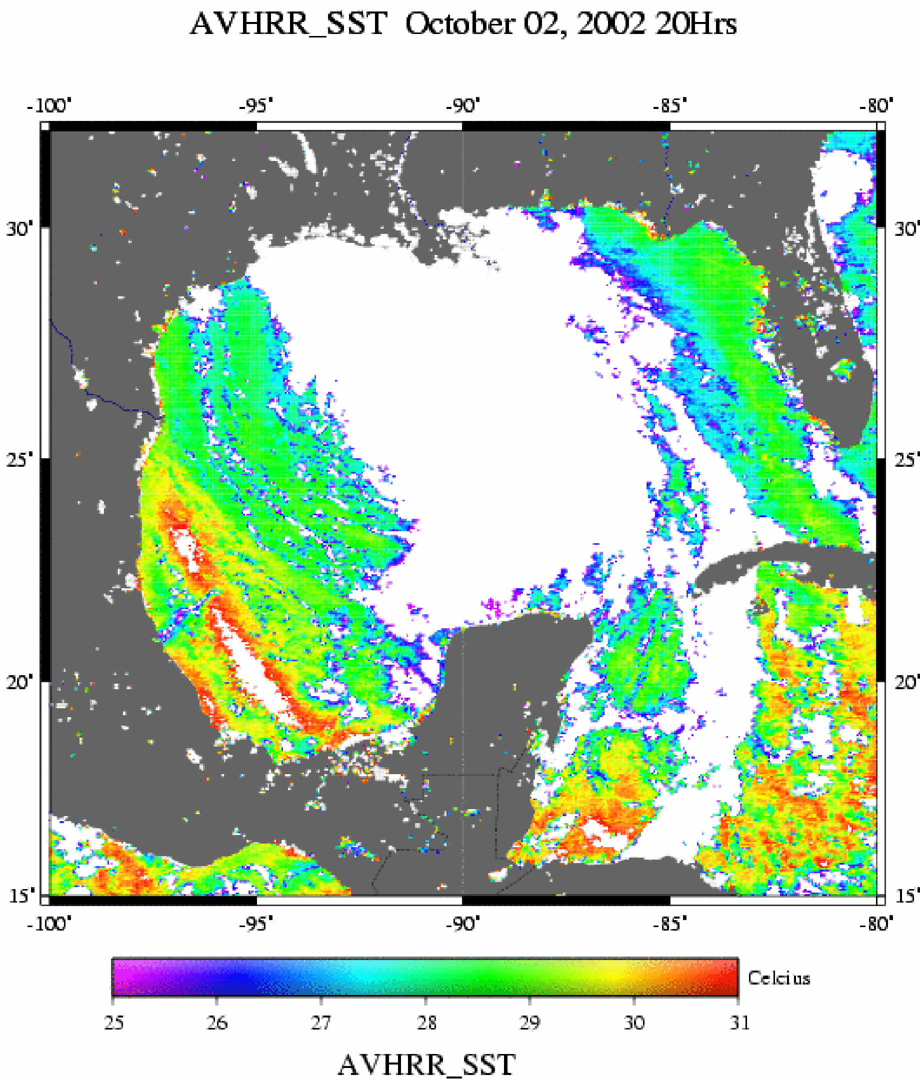
AVHRR Quality Levels (0 – poorest, 7-highest)



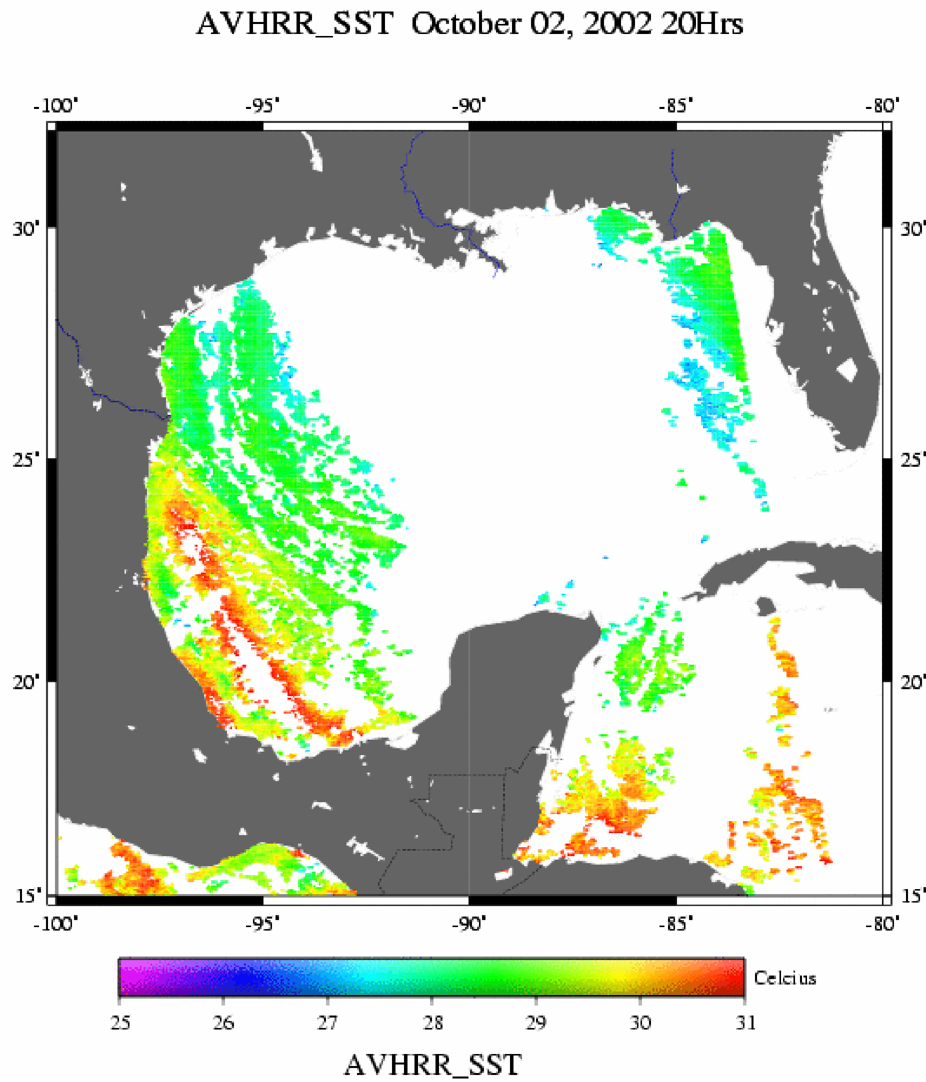
Combination of individual quality tests to derive an overall pixel quality level. The location of the test result in the appropriate mask variable is indicated (in parenthesis) as "MXBY", where X is 1 (mask 1) or 2 (mask 2), and Y is the bit (1-8) in the corresponding mask variable.

Figure duplicated from Page 9194 of the Journal of Geophysical Research, Vol. 106, No. C5, May 15, 2001. Kilpatrick et al. Overview of the NOAA/NASA advanced very high resolution radiometer Pathfinder algorithm for sea surface temperature and associated matchup database.

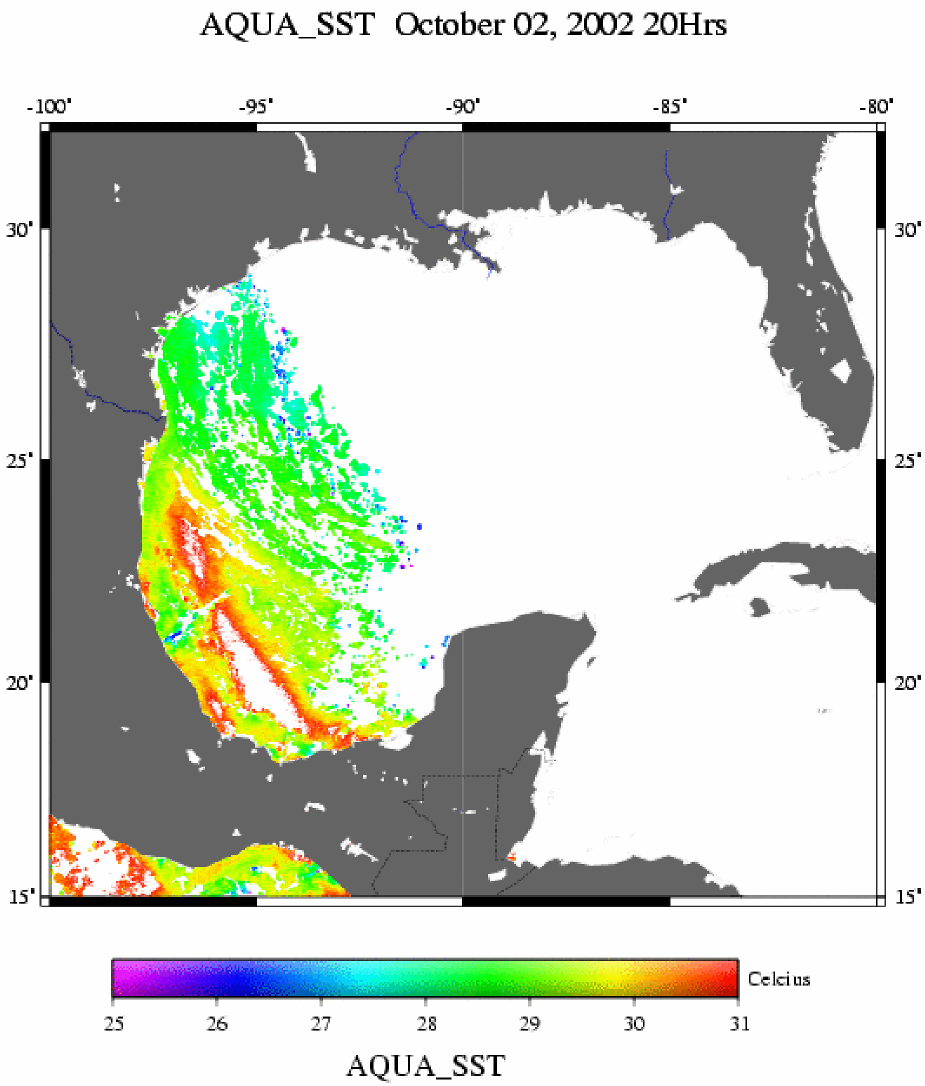
AVHRR (night October 2, 2002)

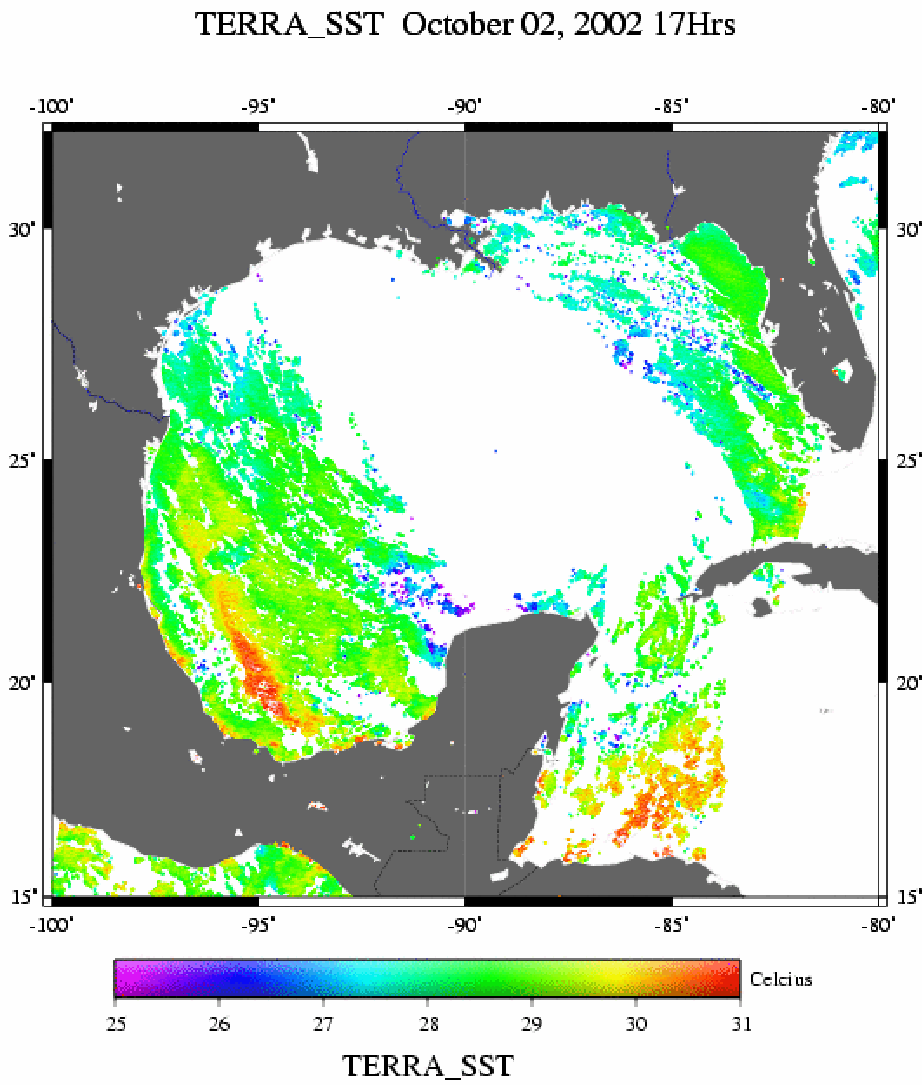


Quality levels 3-7 with land mask



Aqua and Terra (night October 2, 2002)



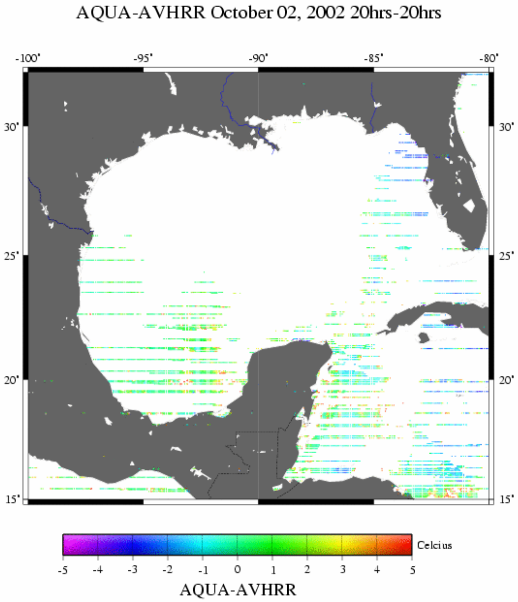


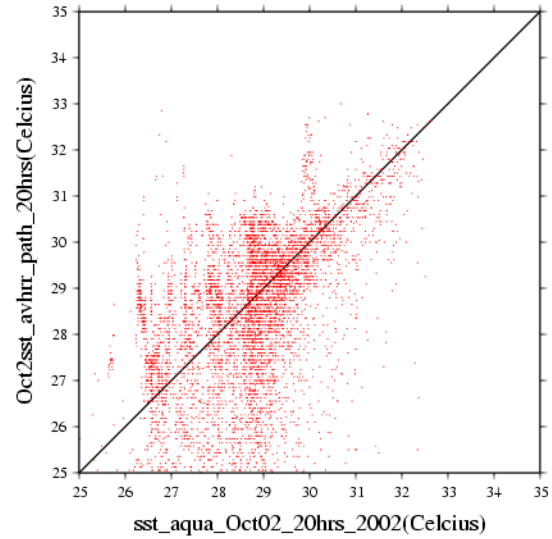
Data Preparation for Comparison
(Aqua vs AVHRR and Terra vs AVHRR)

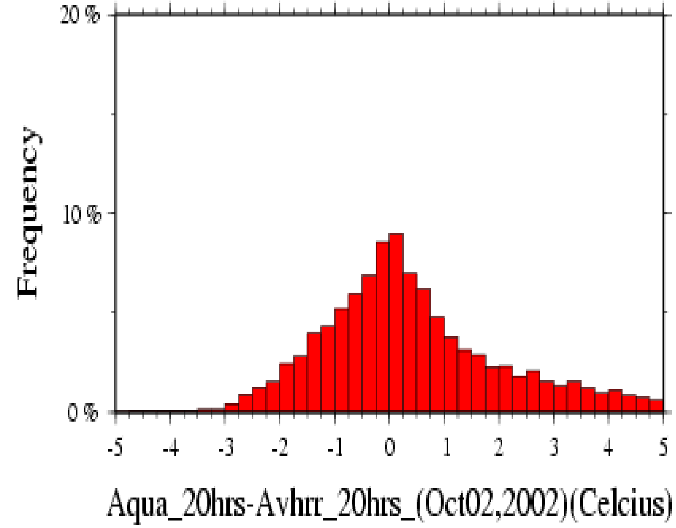
- Interpolate Aqua/Terra SST data to a 4km gridded representation
- Filter all SST data so that SST is between 23 C and 33 C
- Create grid mask for all the SST data
- Create land mask for the specified spatial domain
- Filter AVHRR data to keep quality levels 3-7 only

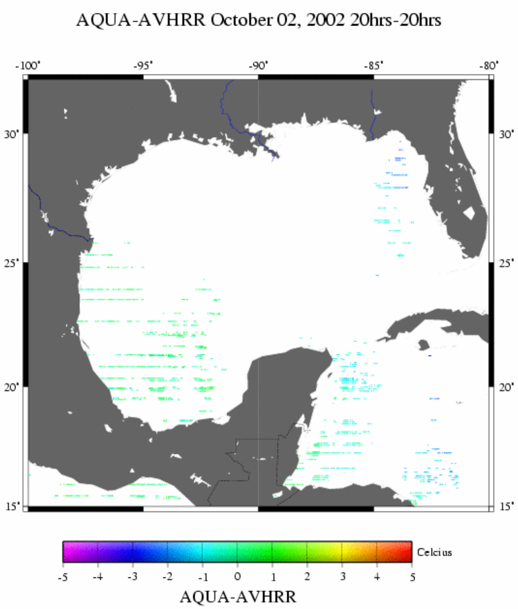
Aqua – AVHRR Difference

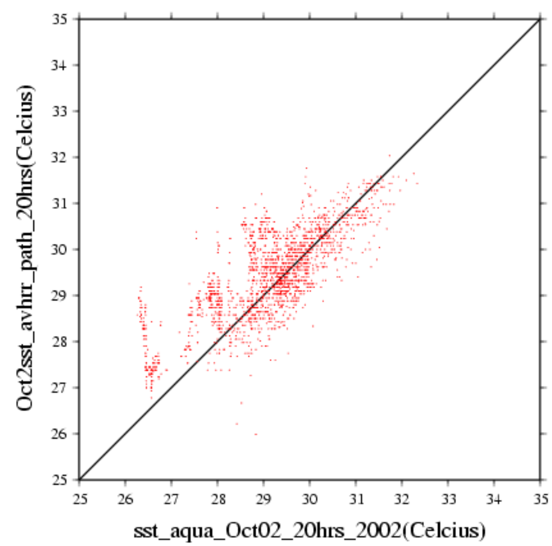
(before & after removing quality levels < 3)

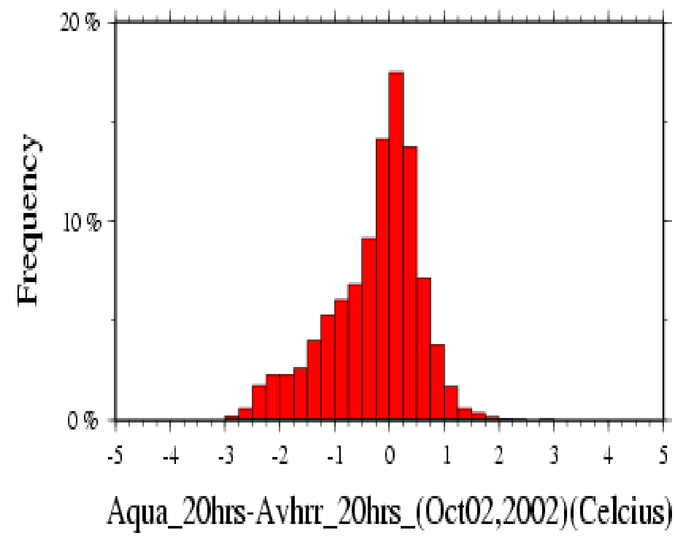






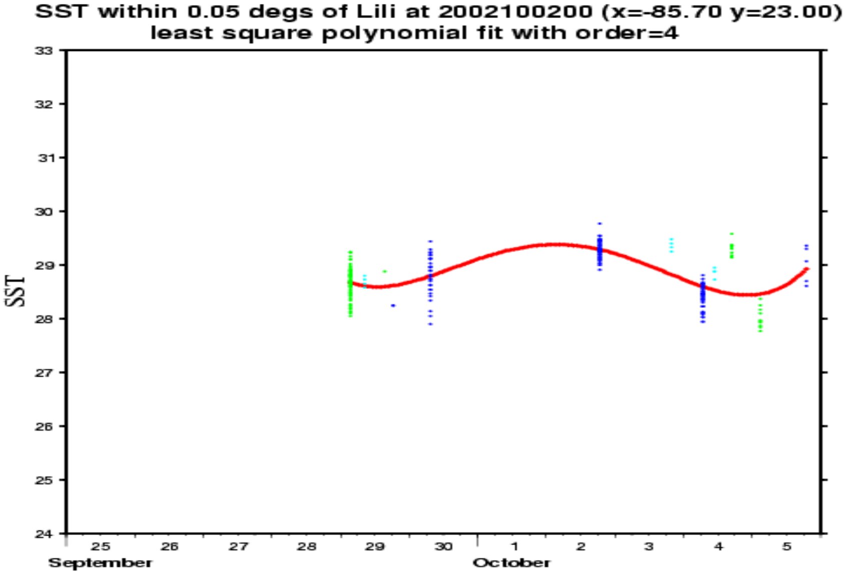


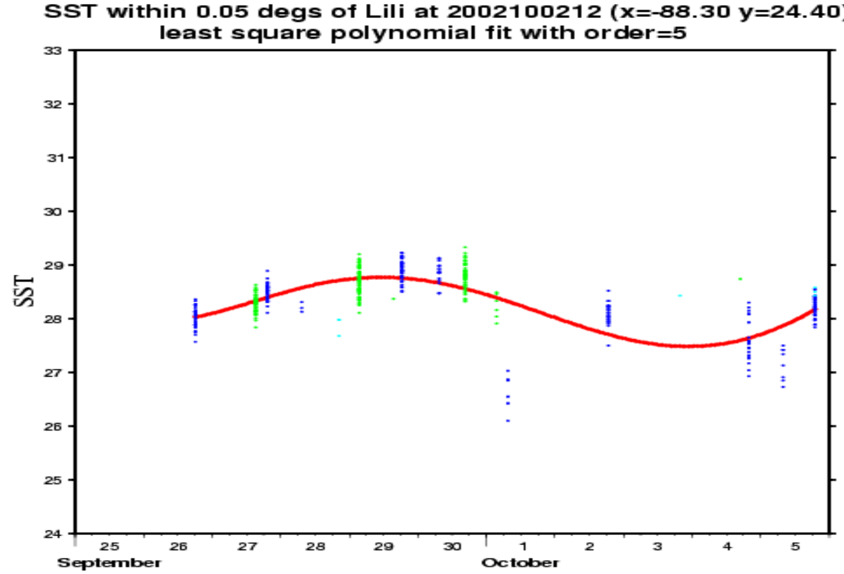


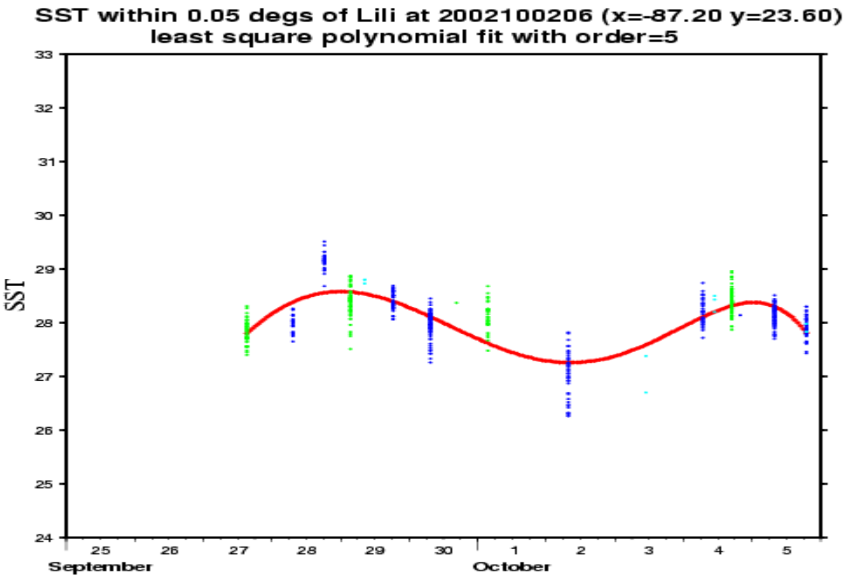


SST Time Series Along Lili’s Track

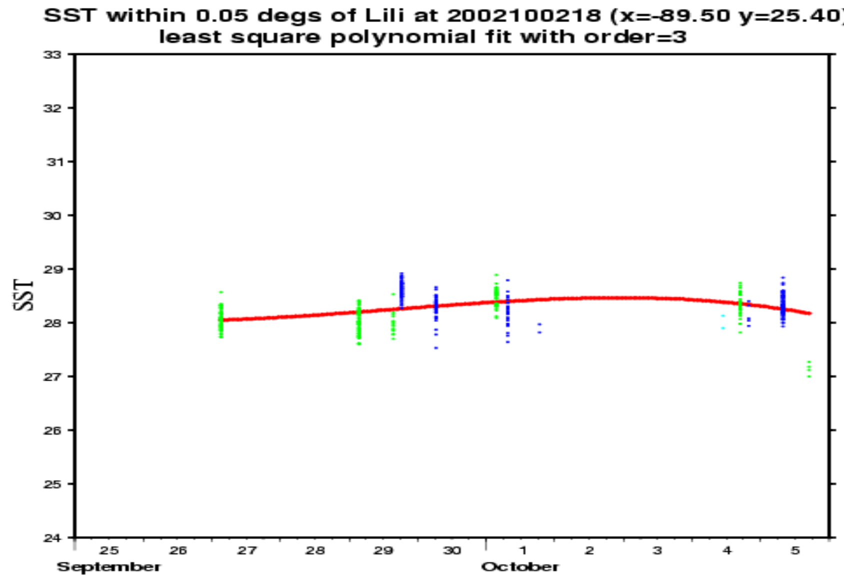
Datasets: Aqua, Terra, AVHRR, TRMM, Buoy







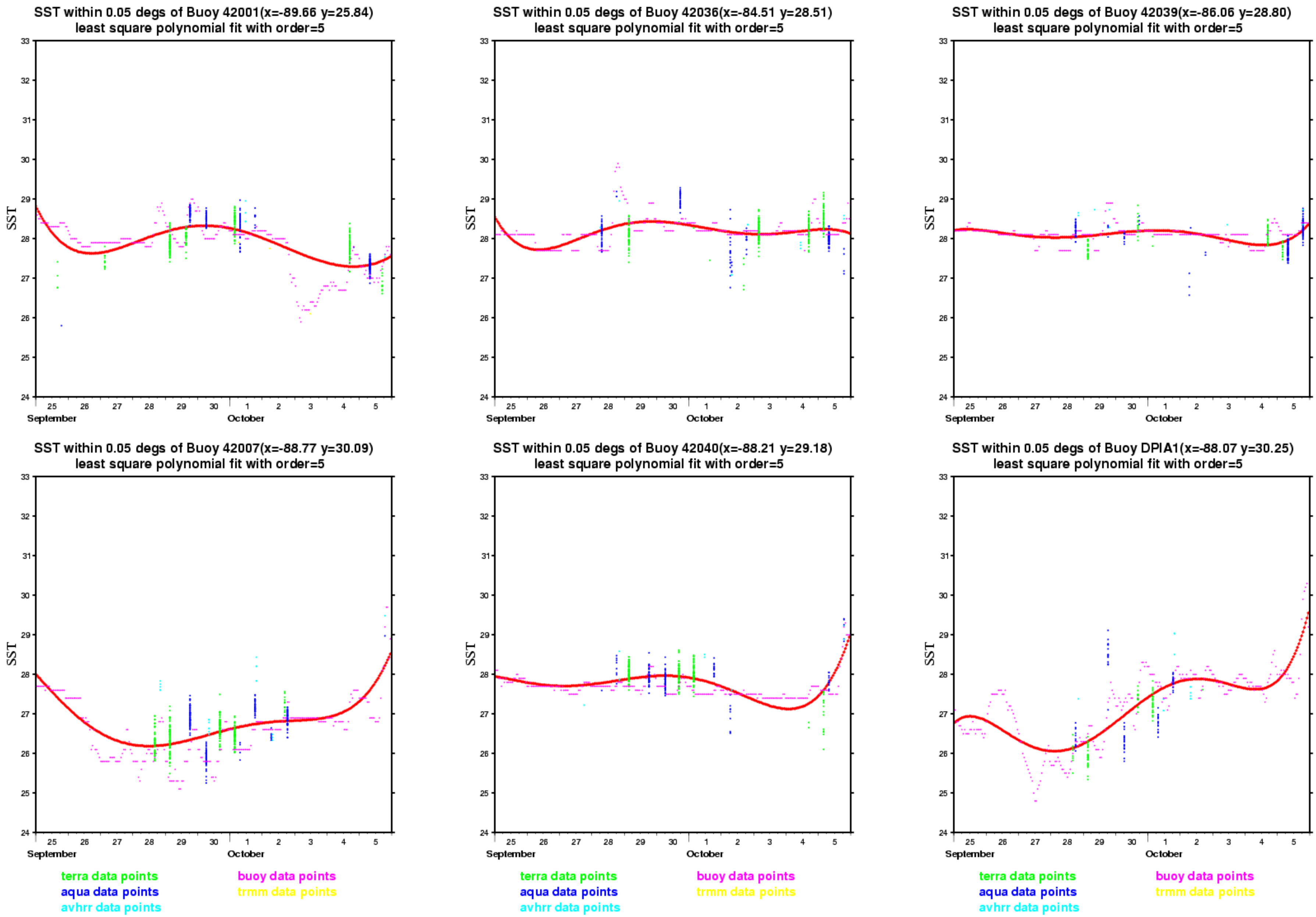
terra data points
aqua data points
avhrr data points
buoy data points
trmm data points



terra data points
aqua data points
avhrr data points
buoy data points
trmm data points

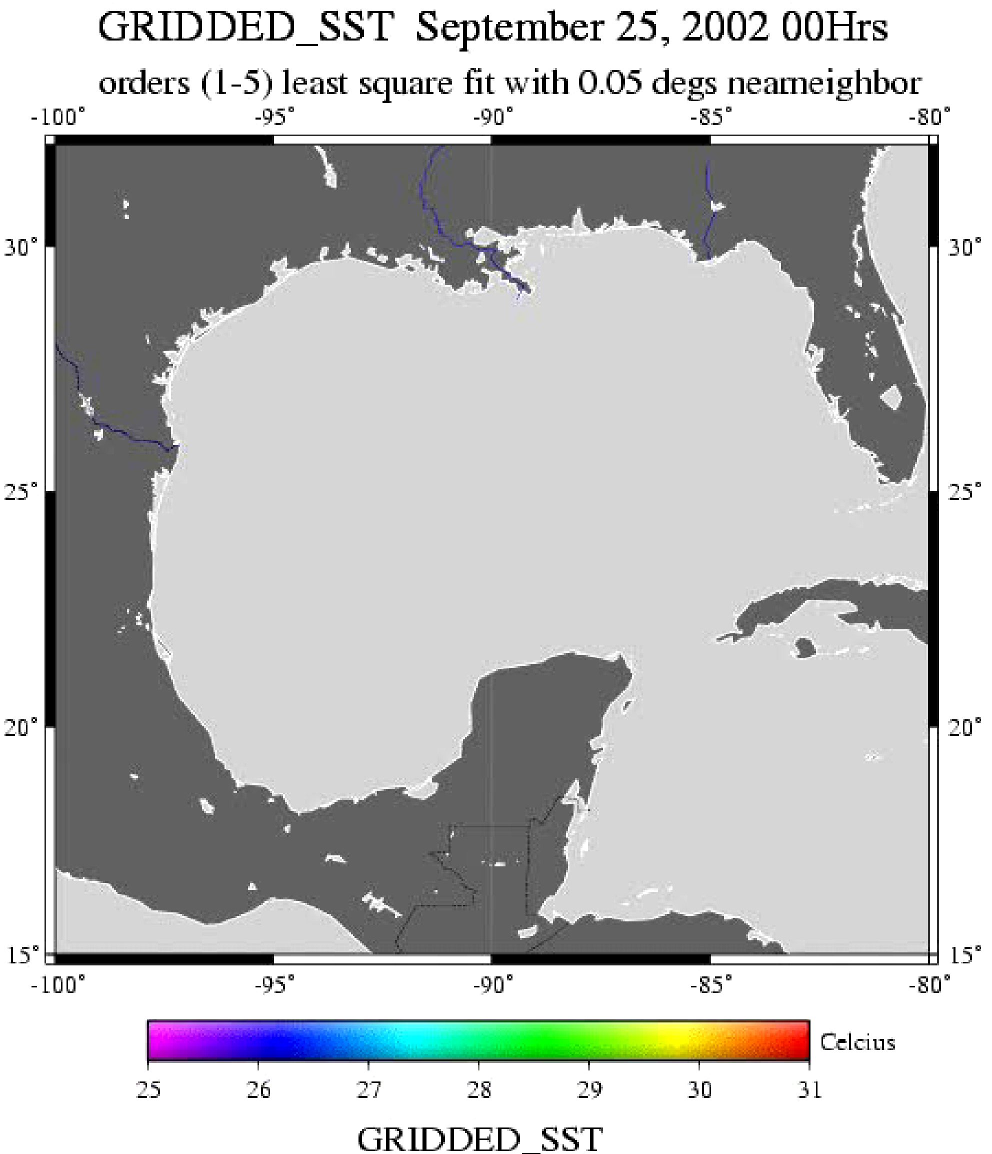
SST Time Series Around Buoys

Datasets: Aqua, Terra, AVHRR, TRMM, Buoy



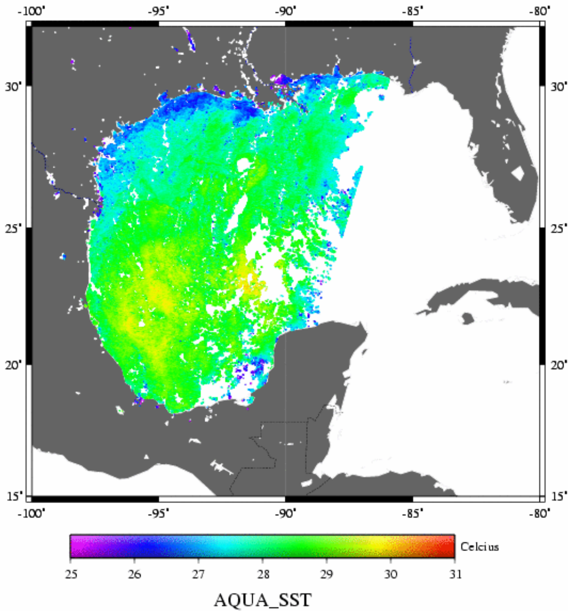
Gridded SST of All Data

- Sept 25, 2005 – Oct 5, 2005
- Data (Aqua, Terra, AVHRR, TRMM, Buoy)
- Grid spacing = 0.02 degrees
- Land mask
- Aqua and Terra data which are colder than the nearest 3 neighbors by less than 0.7 C (Uniformity Test)
- AVHRR data with quality levels 4 to 7
- 23 C < SST < 33 C
- Filled in data points at satellite passes by averaging nearest neighbors with distance up to 0.05 degrees
- Filled in data points between satellite passes using least square polynomial with different orders
- *Goal is to generate a grid of SST data for October 1, 2, and 3.*

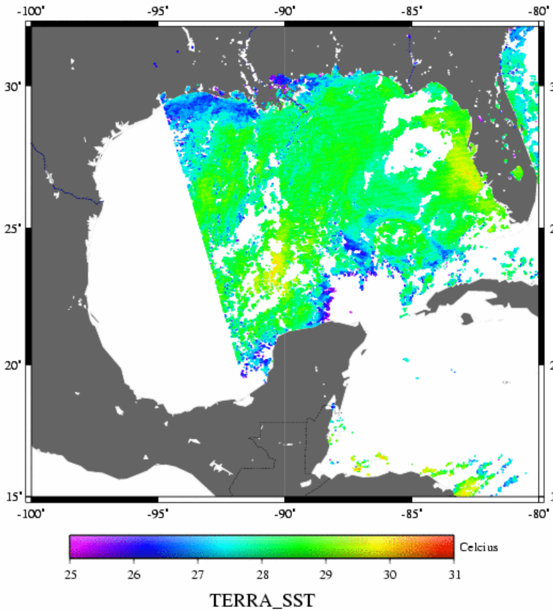


Aqua, Terra, AVHRR, TRMM SST (before & after processing)

AQUA_SST October 01, 2002 08Hrs

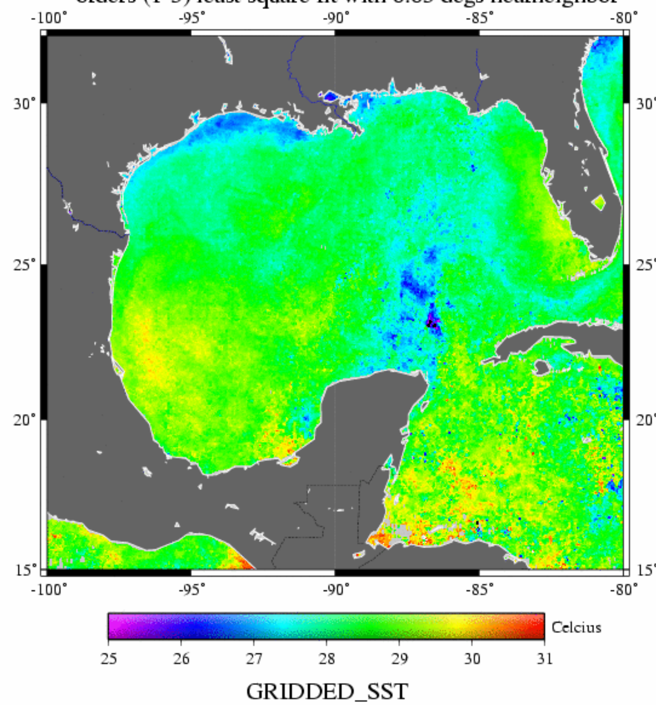


TERRA_SST October 01, 2002 04Hrs

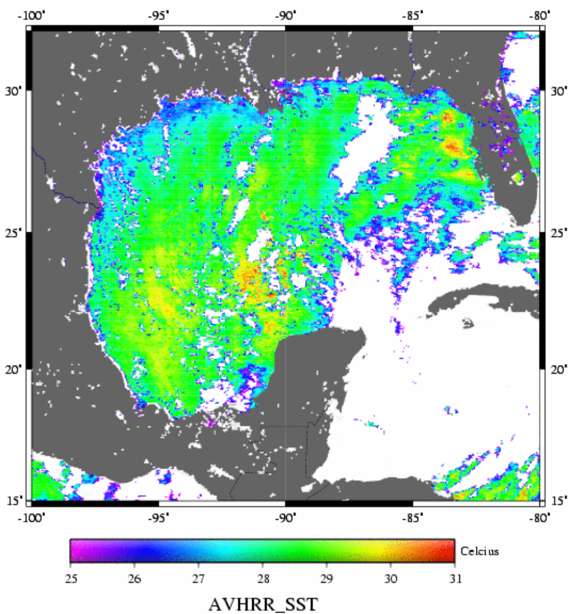


GRIDDED_SST October 1, 2002 08Hrs

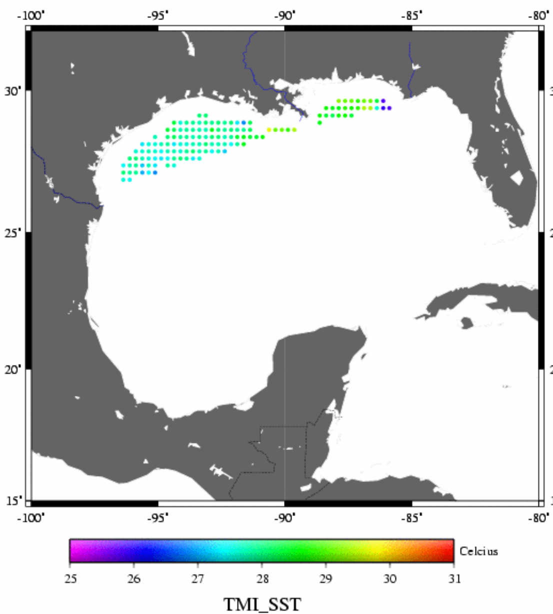
orders (1-5) least square fit with 0.05 degs nearneighbor



AVHRR_SST October 01, 2002 12Hrs

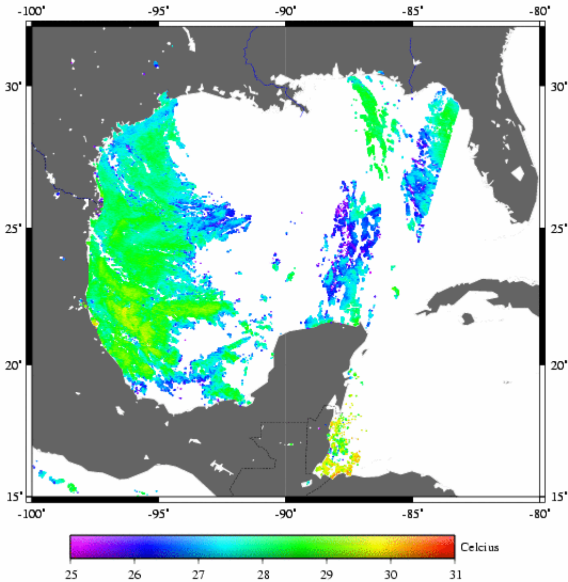


TMI_SST October 01, 2002 08Hrs



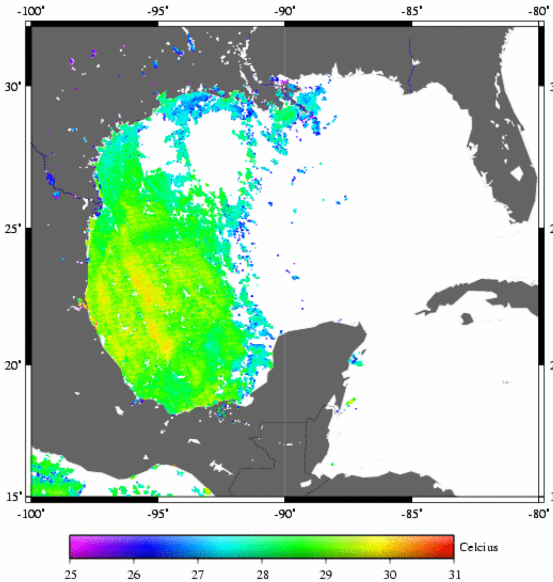
Aqua, Terra, AVHRR, TRMM SST (before & after processing)

AQUA_SST October 02, 2002 08Hrs



AQUA_SST

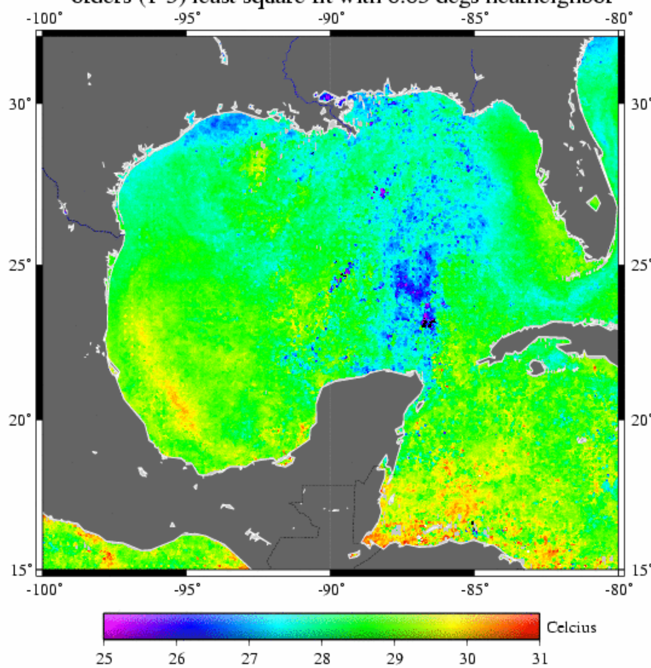
TERRA_SST October 02, 2002 05Hrs



TERRA_SST

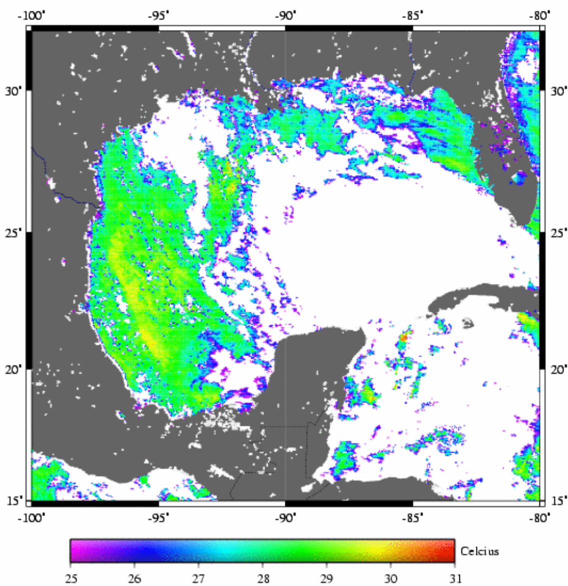
GRIDDED_SST October 2, 2002 08Hrs

orders (1-5) least square fit with 0.05 degs nearneighbor



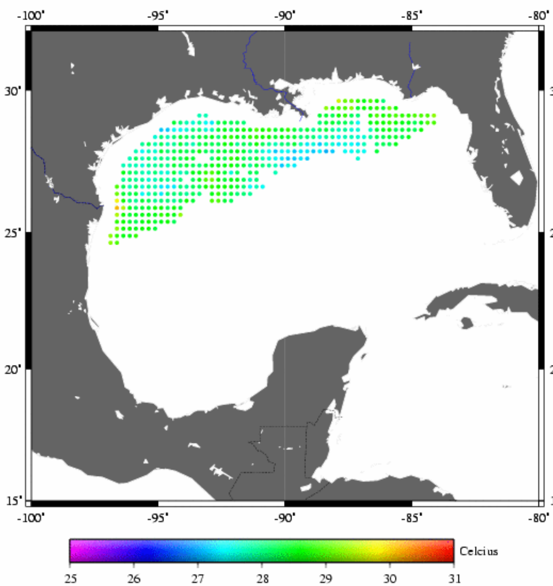
GRIDDED_SST

AVHRR_SST October 02, 2002 08Hrs



AVHRR_SST

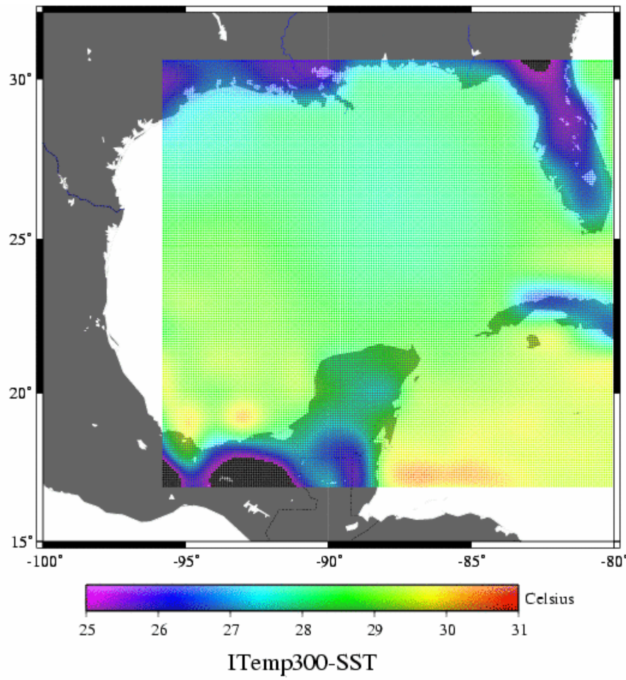
TMI_SST October 02, 2002 08Hrs



TMI_SST

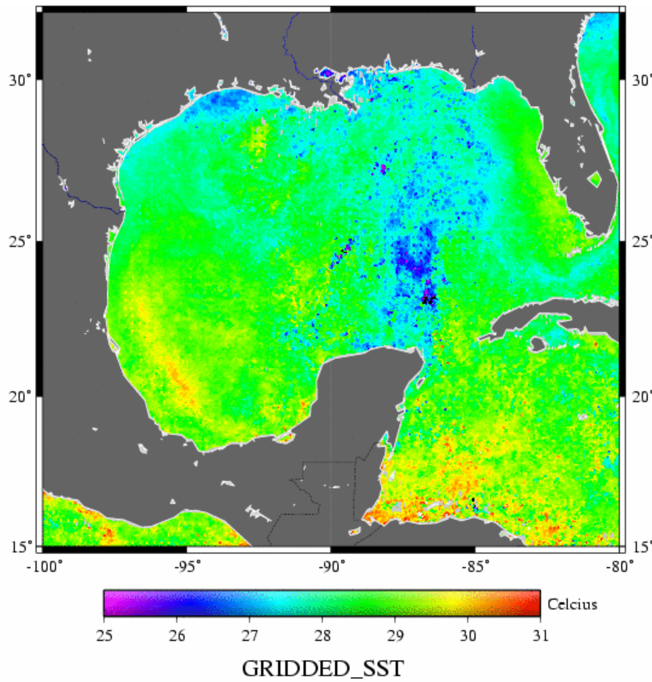
National Weather Service SST versus satellite SST, Oct 2

NWS SST (from AVN)



AVN SST lacks details and SST extremes
Smoothness due to a 7-day running mean, and
an e-folding time of 90 days to dampen anomalies

New SST



Note cold water off Louisiana (caused most of Lili's weakening?)
Note cold wake behind Lili
Note warm water northwest of Yucatan (caused Lili's intensification?)

V. Summary

1) Hurricane Lili simulations conducted using MM5 to examine intensity swings, using 3 domains to 9-km resolution.
2) Sensitivity done using vortex bogussing scheme, T and Td profiles (dropsondes and Terra). QUIKSCAT and cloud-drift winds also used.
3) Cycled assimilation runs conducted using Cressman (MSU, not shown) and 4DVAR (NCAR). The 4DVAR takes 300 hours, and is limited to 81-km and 27-km grids. Cressman done at 9-km as well.
4) T and Td data improve track forecasts considerably, and weakening case a little
5) It is hypothesized that the new satellite SST data will improve the Hurricane Lili intensity simulation. This work is ongoing.

VI. Commercial potential

1) Code for data cycling
2) QC algorithms
3) Cressman assimilation scheme
4) 4DVAR assimilation scheme
5) Gridded SST algorithm using multiple satellites
6) Algorithms to process NASA satellite data in hdf format