# NWP in the U. S. Navy

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## Outline

- History of NWP in the Navy
- Current Status
- Future Plans
- Concluding Remarks

# NWP in the U. S. Navy

## History of Modeling: Global

| Year | Computer | GFLOPS | Model | Data Assimilation |
|---|---|---|---|---|
| 1974 | CDC 6500 (2-p) | 0.003 | | |
| 1975 | | | | |
| 1976 | CDC Cyber 175 | 0.01 | | |
| 1977 | | | NHPE: 381 km/L5 | Fields-By-Information Blending |
| 1978 | | | | |
| 1979 | | | | |
| 1980 | CDC Cyber 203 | 0.2 | | |
| 1981 | CDC Cyber 205 | | | |
| 1982 | 2nd pipe added | 0.4 | NOGAPS Grid Point: 4°x5°L6 | |
| 1983 | | | 4°x3°L6 | |
| 1984 | | | 2.4°x3°L6 | Variational Balancing |
| 1985 | | | | |
| 1986 | | | | |
| 1987 | 2 pipes added | 0.8 | 2.4°x3°L6 | |
| 1988 | | | NOGAPS Spectral: T47L18 | Multivariate Optimum Interpolation |
| 1989 | | | T79L18 | |
| 1990 | | | | TC Initialization |
| 1991 | Cray c90 (8-p) | 8 | | |
| 1992 | | | | |
| 1993 | | | | |
| 1994 | | | T159L18 | |
| 1995 | | | | |
| 1996 | 2nd 16-p c90 added | 24 | | HiRes Feature Track Winds |
| 1997 | | | | |
| 1998 | | | T159L24 | |
| 1999 | | | | |
| 2000 | | | Emanuel Cumulus | |
| 2001 | SGI O3000 (512-p) | 1000 | | |
| 2002 | | | T239L30, MPI | |
| 2003 | SGI: 512/128/256/256-p | 2600 | NAAPS (Aerosols) | NAVDAS |
| 2004 | IBM: 288-p added | 4400 | | Direct Assimilation of AMSU-A |

# NAVDAS

## NRL Atmospheric Variational Data Assimilation System

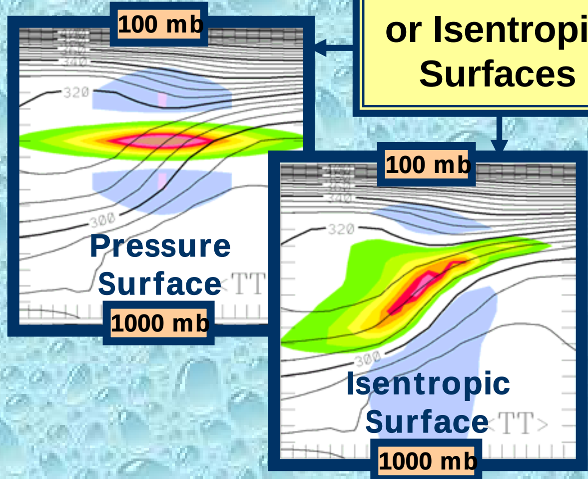
**Focus:** Optimal fit of observational and model data

**Observations** | **Background**

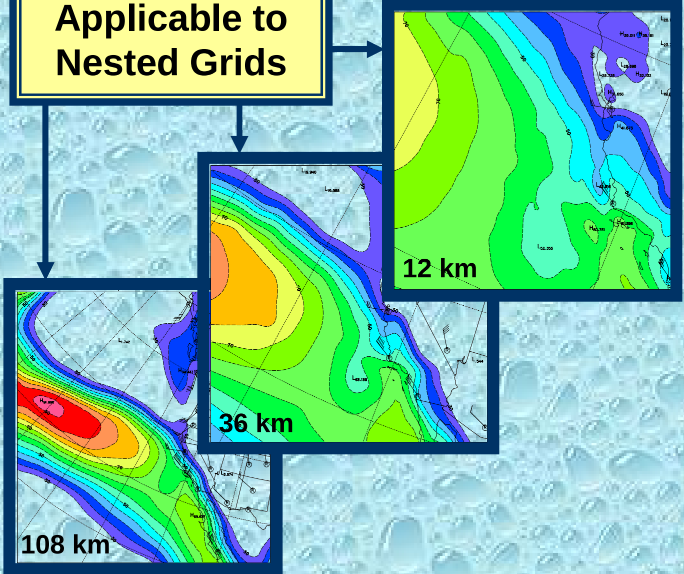
$$J_o = \left(y - H(x_a)\right)^T R^{-1}\left(y - H(x_a)\right) + \left(x_a - x_b\right)^T P_b^{-1}\left(x_a - x_b\right)$$

NAVDAS minimizes the cost function $J_o$ where $x_a$ is the analysis, $x_b$ is the background, H is the forward model, y is the observations, R is the observational error covariance, and $P_b$ is the background error covariance

Applicable to Pressure or Isentropic Surfaces



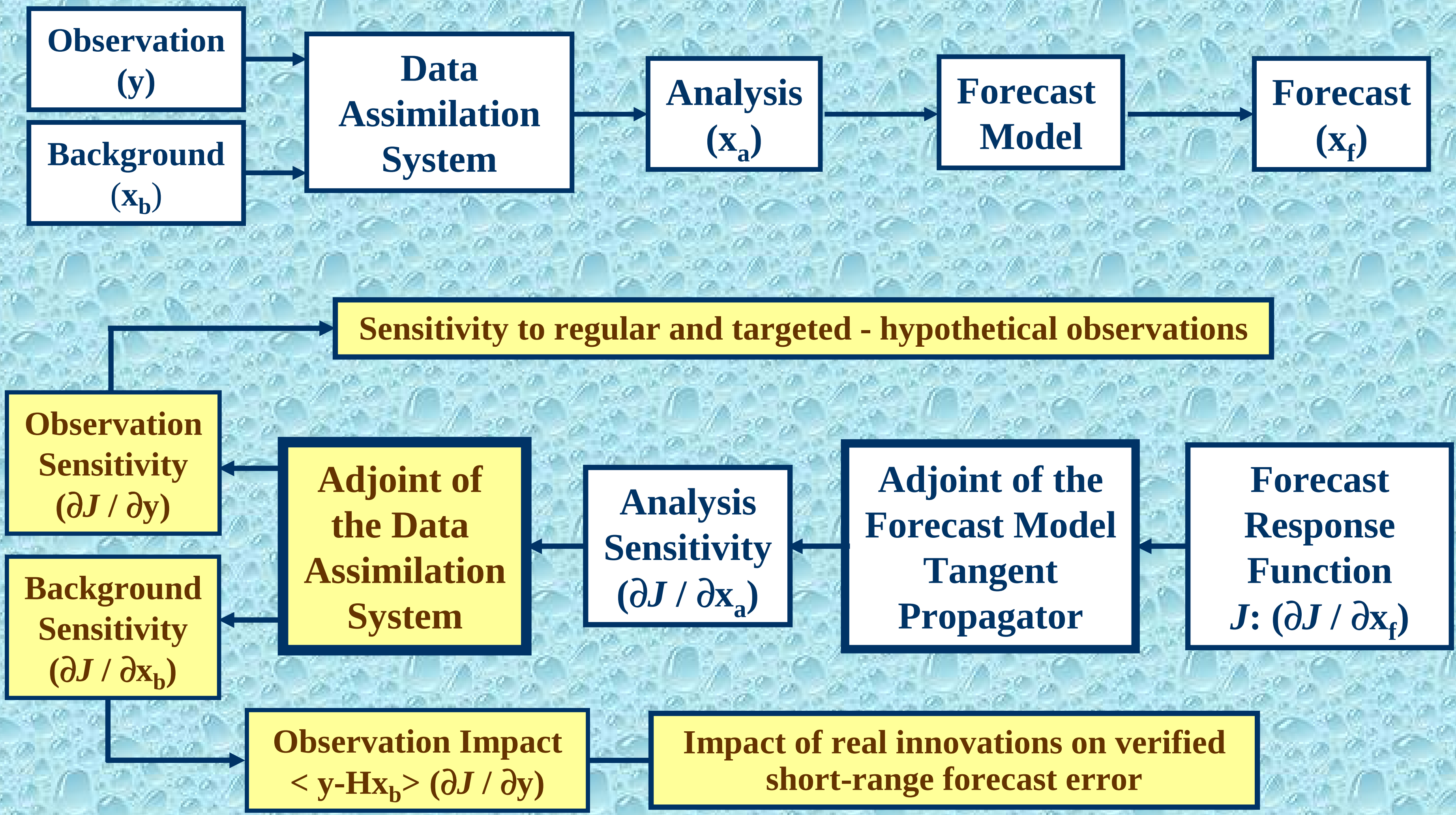

Applicable to Nested Grids




- **Analysis variables:** Temperature, Height, u- and v-wind components, Wind speed, Moisture, and Radiances, from the surface to 0.1 mb (~65 km)
- **Satellite data:**
  - **Operational:** AMSU-A, SSMI TPW, MODIS winds, Cloud and Water Vapor winds
  - **Beta-Testing:** AMSU-B, HIRS, SSMI winds, QuikSCAT, WindSat
- **Features:**
  - Cast in observation space
  - Most efficient for sparse observations/dense grids
  - Runs on mainframes or workstations (uses MPI and FORTRAN)
  - Applicable to any model or grid (global or mesoscale)
- **Operational at FNMOC: Oct 2003**

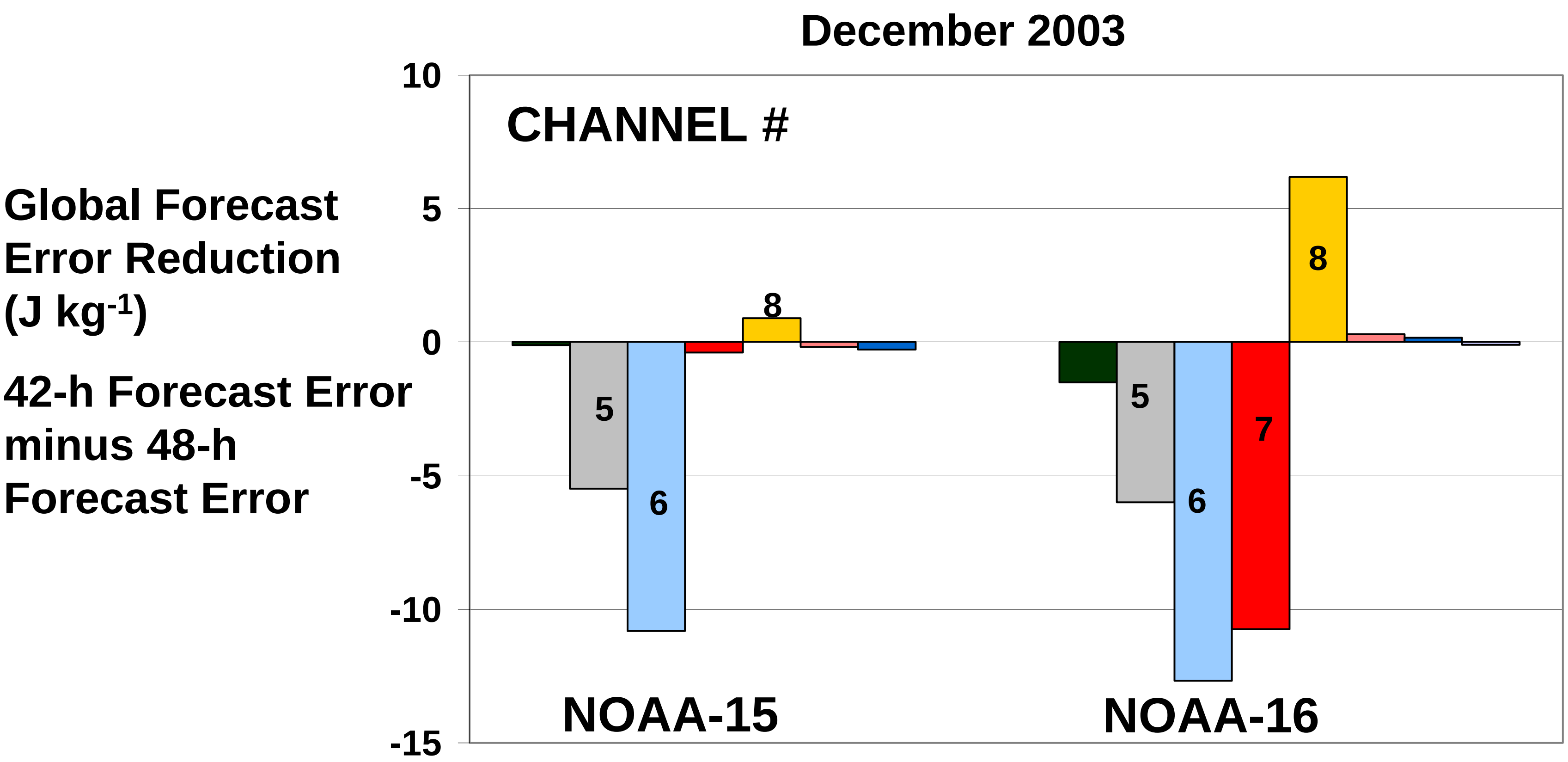
# NAVDAS Adjoint

**NAVDAS: NRL Atmospheric Variational Data Assimilation System**



# Observation Impact using the NAVDAS Adjoint

*Rolf Langland and Nancy Baker*



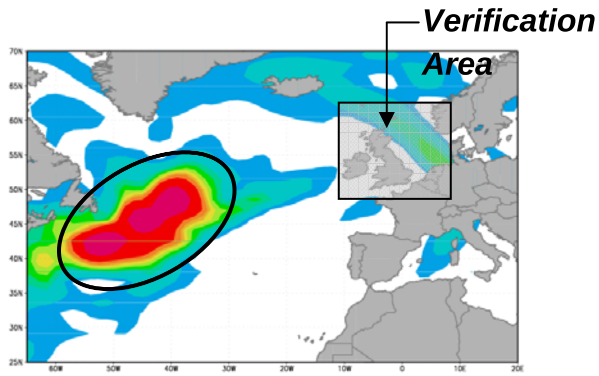

***NOGAPS and NAVDAS adjoints allows one to calculate sensitivity of forecast to changes in the analysis AND changes in the observations***

# Observation Impact using the NAVDAS Adjoint

**Forecast Response Function $J$: $(\partial J / \partial x_f)$**

→ **Adjoint of the Forecast Model Tangent Propagator**

→

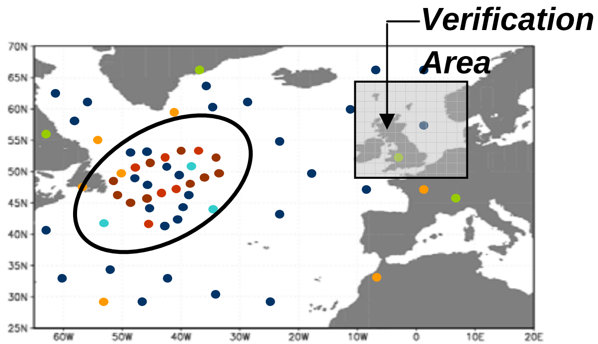



**Sensitivity of "J" to Initial Temperature on Model Grid**

↓

**Adjoint of the Data Assimilation System**

→




**Sensitivity of "J" to Observations that will be Assimilated**

*Source: Langland & Baker, 2004*

# NOGAPS

**Navy Operational Global Atmospheric Prediction System**

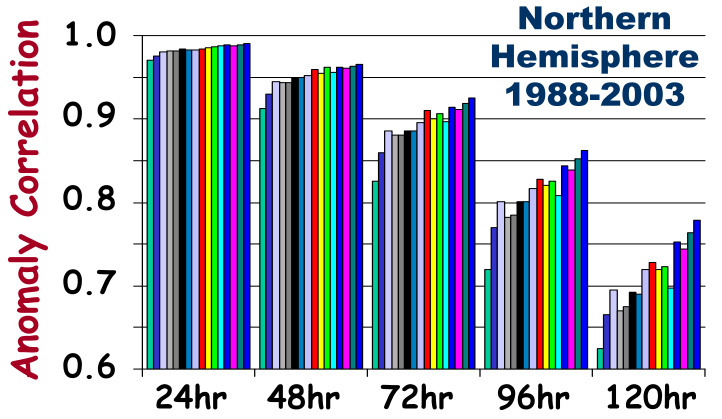
**0-6 day global forecasts**

- **Complex Data Quality Control**
- **Analysis:**
  - **NRL Atmospheric Variational Data Assimilation System** (NAVDAS)
  - **2-d OI Analysis of SST** (NRL Coastal Data Assimilation System, NCODA)
- **Nonlinear, Normal Mode Initialization**
- **Hydrostatic, Spectral Atmospheric Model:**
  - **Cumulus Parameterization** (Emanuel, MWR 1999)
  - **PBL Parameterization** (Louis, BLM 1979)
  - **Radiation Parameterization** (Harshvardhan et. al., JGR 1987)
  - **Convective and Stratiform Cloud Parameterization** (Teixeira and Hogan, JC 2002)
  - **Gravity Wave Drag** (Webster et. al., QJRMS 2003)
- **Features:**
  - **Over 17,000 Operational Forecasts run at FNMOC since 1982**
  - **6 Hour Incremental Data Assimilation Cycle**
  - **Current Operational Resolution:** T239 (~55 km), 30 Vertical Levels
  - **Approximately 7.5 minutes/forecast day wall time using 120 O3K processors**
  - **Track Forecasts for all Tropical Cyclones w/max wind > 50 knots**
  - **Supplies Boundary Conditions to Mesoscale and Wave Models**

# NOGAPS Annual Mean Forecast Statistics

**Anomaly Correlation* of 500 mb Heights**

**Values Greater than 0.6 are Considered Skillful**




## NOGAPS:

**Navy Operational Global Atmospheric Prediction System**

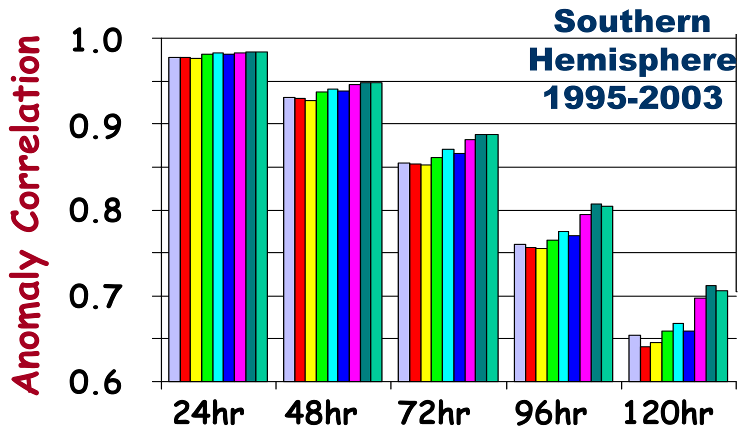
**NH Colors**

- 1988
- 1989
- 1990
- 1991
- 1992
- 1993
- 1994
- 1995
- 1996
- 1997
- 1998
- 1999
- 2000
- 2001
- 2002
- 2003

*Anomaly Correlation: $\dfrac{\sum(f-c)(a-c)}{\sqrt{\sum(f-c)^2(a-c)^2}}$

Key:

- f: forecast
- c: climatology
- a: analysis



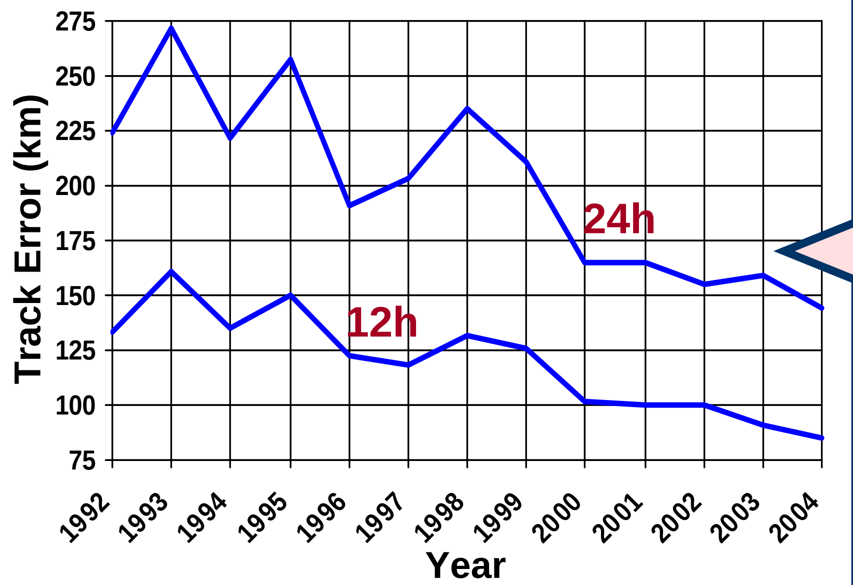

**SH Colors**

- 1995
- 1996
- 1997
- 1998
- 1999
- 2000
- 2001
- 2002
- 2003

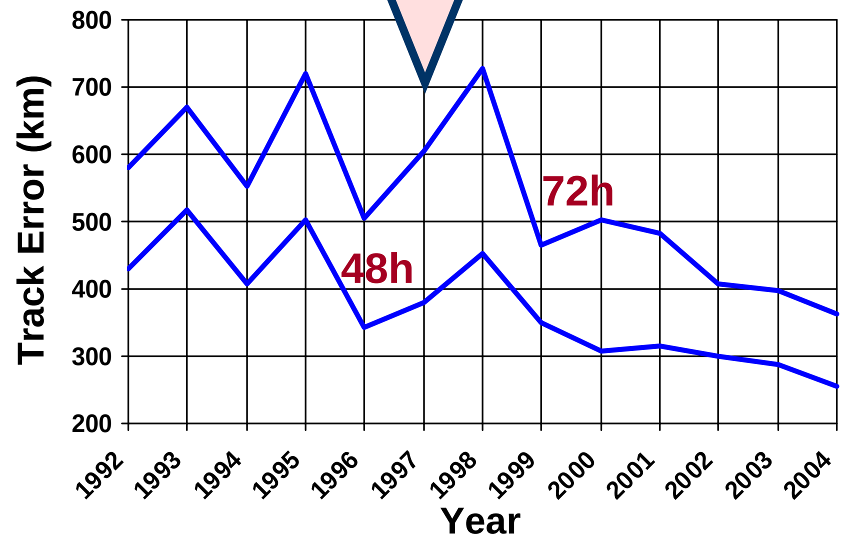
***Results indicate that forecast skill is improving at the rate of about one day per decade***

# NOGAPS Historical TC Forecast Track Error

## Western North Pacific



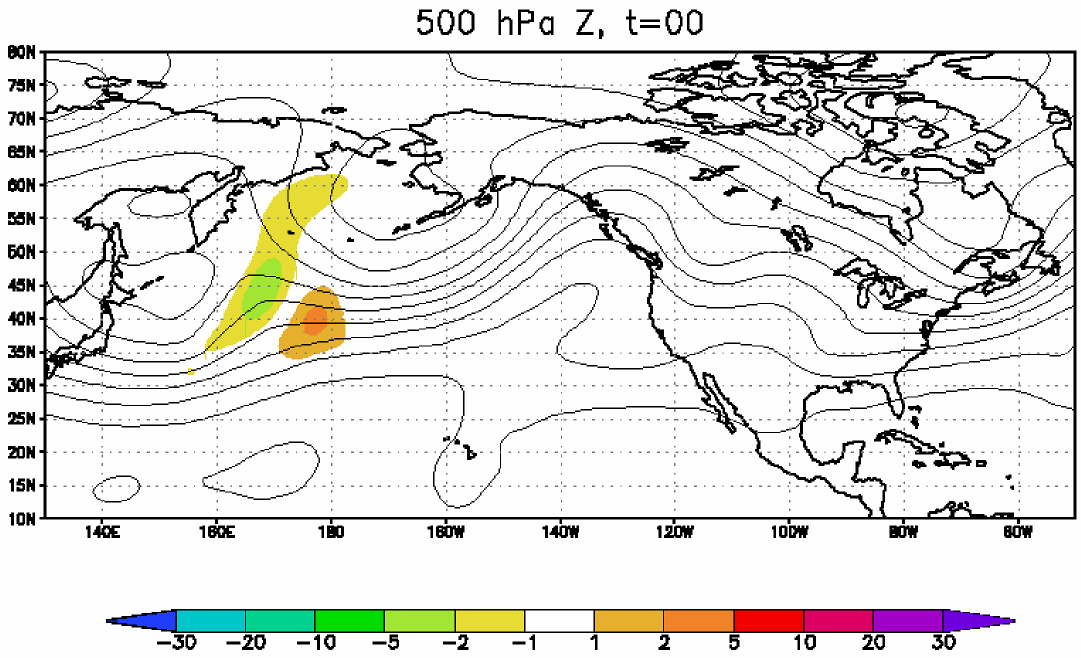

***Current 24h (72h) errors are comparable to 12h (48h) errors from 10 years ago***




***Error reduction is attributed to upgrades in model physics, data assimilation, and model resolution***

# Growth of perturbations and errors in the SV-subspace over 3-days

**Leading Singular Vector (SV):** Fastest growing (linear) perturbation to a trajectory




**Initial perturbations ~ 1 m** **Final perturbation > 40 m**

**Relevance for NWP, Rapid growth (x25 in 3 days), Rapid propagation (30°/day), Function of metric**

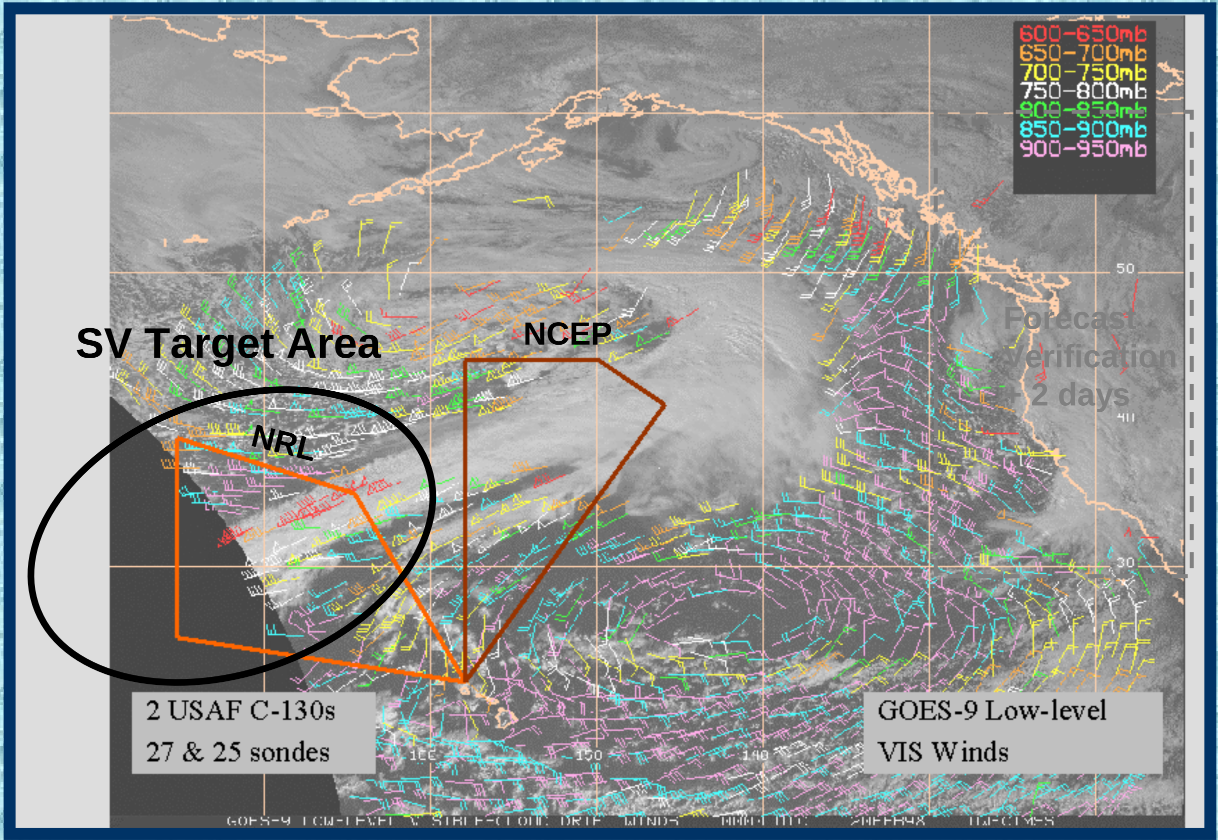
# Targeting Field Programs

**NORPEX 1998**

**Targeting Methods:**

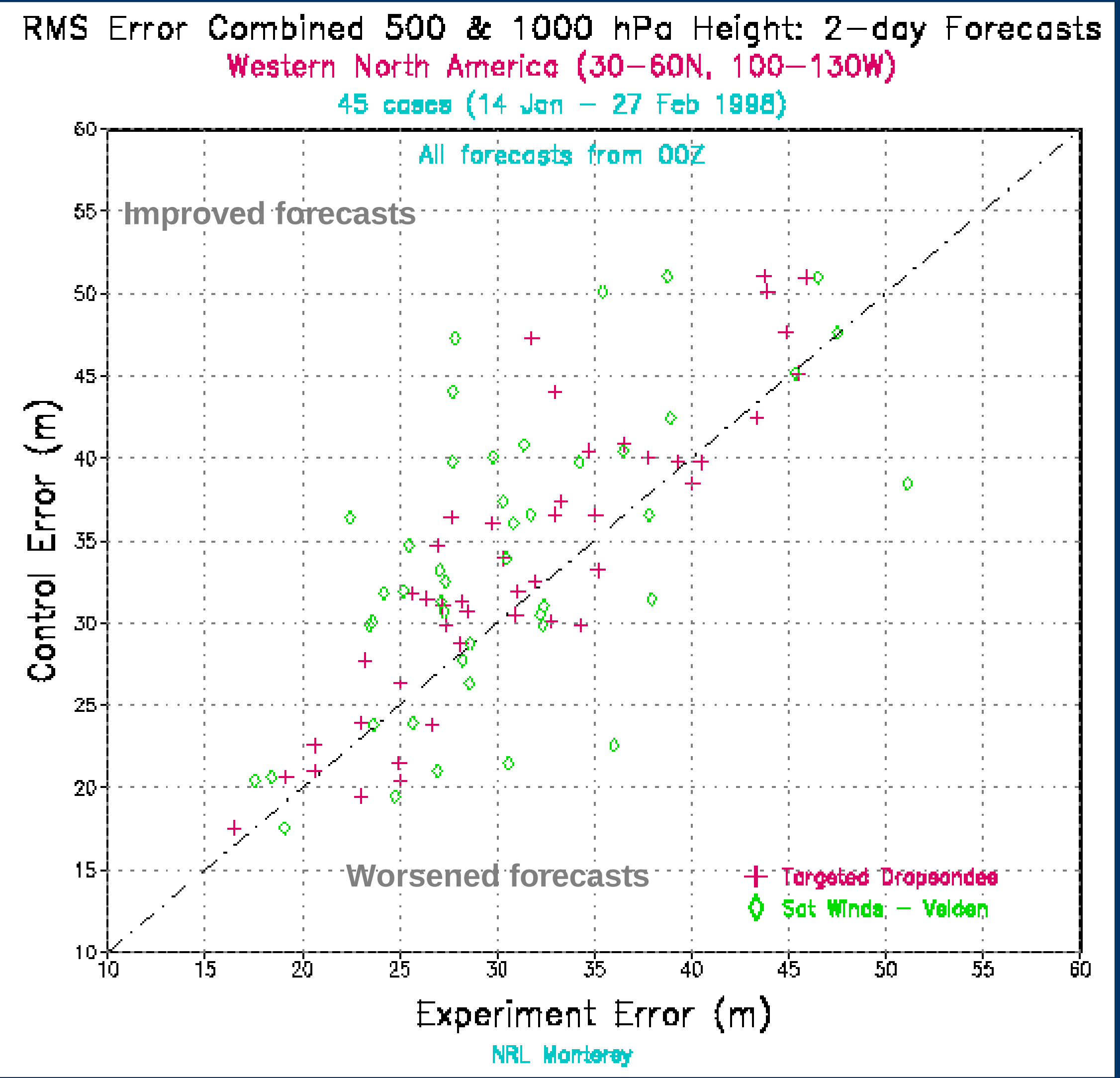
**NRL:** e-norm singular vectors and adjoint-derived sensitivity gradients

**NCEP:** ETKF



# Targeting Field Programs

## NORPEX 1998 Targeting Result




Dropsondes provided an average 8% reduction in 2-day 500 hPa height error over western North America

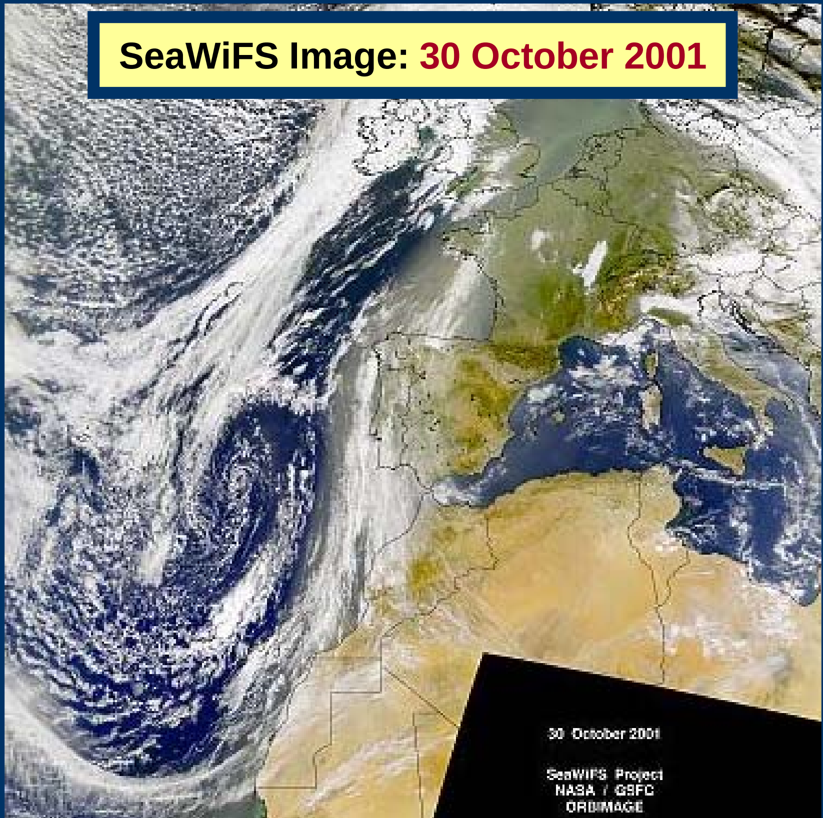
Targeted observations improve forecasts on average, but not in every case

Satellite winds were tested as proxy targeted observations - Impact was similar to that from dropsonde observations

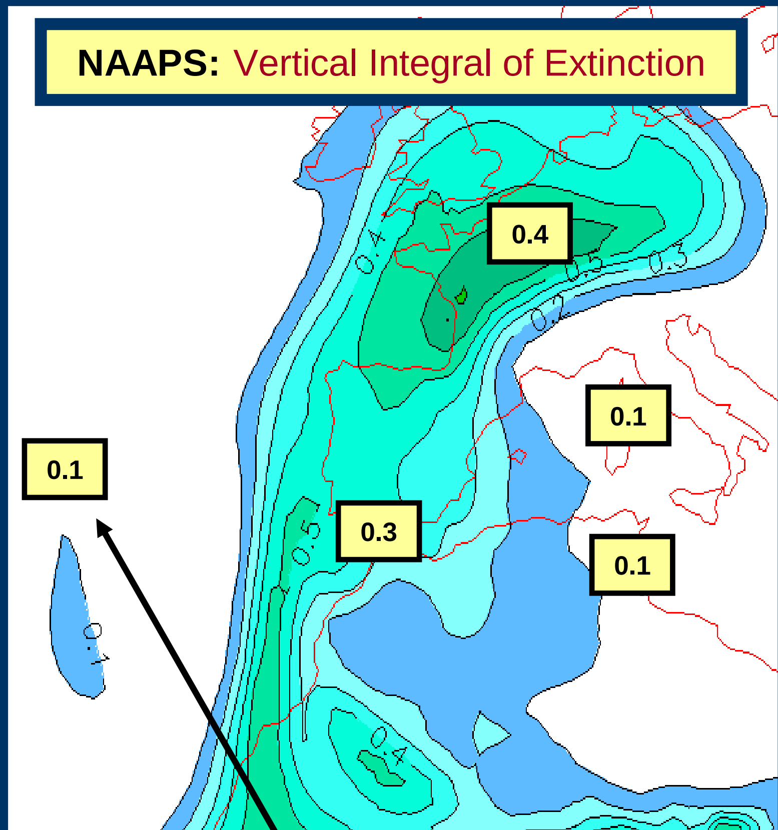
# **NAAPS:** NRL Aerosol Analysis and Prediction System

## *Global Aerosol Modeling:* Validation of NAAPS Using SeaWiFS and AERONET Data

**SeaWiFS Image: 30 October 2001**




**NAAPS:** Vertical Integral of Extinction





**AERONET Observation**
**Network of sun photometers**

# NWP in the U. S. Navy

## History of Modeling: Mesoscale

| Year | Computer | GFLOPS | Model | Data Assimilation |
|---|---|---|---|---|
| 1974 | CDC 6500 (2-p) | 0.003 | | |
| 1975 | | | TC Channel Model: 205kmL3 | |
| 1976 | CDC Cyber 175 | 0.01 | | |
| 1977 | | | | |
| 1978 | | | | |
| 1979 | | | OTCM: 205kmL3 | Cold Starts |
| 1980 | CDC Cyber 203 | 0.2 | | |
| 1981 | CDC Cyber 205 | | | |
| 1982 | 2nd pipe added | 0.4 | NORAPS: 120kmL10 | |
| 1983 | | | | |
| 1984 | | | | |
| 1985 | | | | |
| 1986 | | | | Successive Corrections |
| 1987 | 2 pipes added | 0.8 | 80kmL21 | |
| 1988 | | | | Multivariate Optimum Interpolation |
| 1989 | | | | |
| 1990 | | | | TC Initialization |
| 1991 | Cray c90 (8-p) | 8 | 40kmL30 | |
| 1992 | | | | |
| 1993 | | | | |
| 1994 | | | | |
| 1995 | | | Nested Grids: 45/15kmL30 | |
| 1996 | 2nd 16-p c90 added | 24 | | HiRes Feature Track Winds |
| 1997 | | | COAMPS run on USS Nimitz | |
| 1998 | | | COAMPS: 81/27/9kmL30 | |
| 1999 | | | 81/27/9/3kmL30 | |
| 2000 | | | | |
| 2001 | SGI O3000 (512-p) | 1000 | MPI | |
| 2002 | | | 54/18/6kmL30 | |
| 2003 | SGI: 512/128/256/256-p | 2600 | Moving Nested Grids | |
| 2004 | IBM: 288-p added | 4400 | Aerosols | NAVDAS |

# COAMPS™

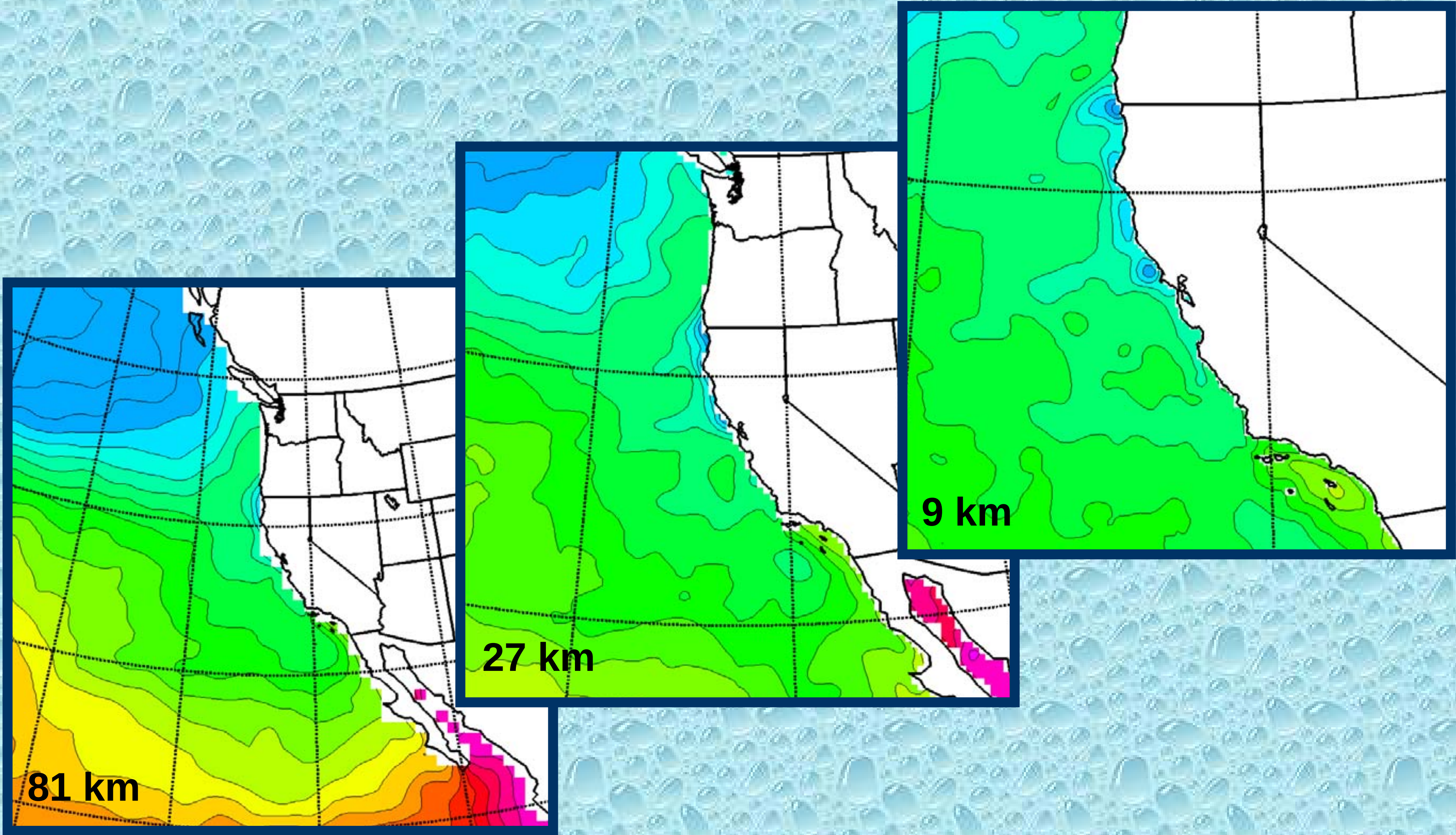
**Coupled Ocean/Atmosphere Mesoscale Prediction System**
**0-3 day high-resolution forecasts**

- **Complex Data Quality Control**
- **Analysis:**
  - **Atmosphere:** MVOI analyses of u, v, and Heights; Univariate analyses of T, q
  - **Ocean:** 2D OI of SST; 3D MVOI of T, S, SSH, Sea Ice, and Currents (NCODA)
- **Initialization:**
  - **Atmosphere:** Hydrostatic Constraint on Analysis Increments, and/or Digital Filter
  - **Ocean:** Stability check
- **Model:**
  - **Atmosphere:**
    - **Numerics:** Nonhydrostatic, Scheme C, Nested Grids, Sigma-z, Flexible Lateral BCs
    - **Parameterizations:** PBL, Convection, Explicit Moist Physics, Radiation, Surface Layer
    - **Aerosols:** Surface databases, High-order Transport, Dry Deposition, Wet Removal
  - **Ocean:** NRL Coastal Ocean Model (NCOM)
    - **Numerics:** Hydrostatic, Scheme C, Nested Grids, Hybrid Sigma/z
    - **Parameterizations:** Mellor-Yamada 2.5
- **Features:**
  - **Globally Relocatable** (5 Map Projections)
  - **User-Defined Grid Resolutions, Dimensions, and Number of Nested/Parent Grids**
  - **Incremental Data Assimilation; Atmosphere: 6 or 12 hours; Ocean: 12 or 24 hours**
  - **Applicable for Idealized or Real-Time Applications**
  - **Single Configuration Managed System for All Applications**
- **Operations** (Atmospheric Components plus 2D SST Analysis):
  - **FNMOC:** 8 Areas, 4 runs/day, grid spacing as low as 6 km, forecasts to 72 hours, 30 levels
  - **Navy Regional Centers:** 2 runs/day, grid spacing as low as 3 km, forecasts to 48 hours

# NCODA SST Analyses for Triply-Nested Eastern Pacific Area

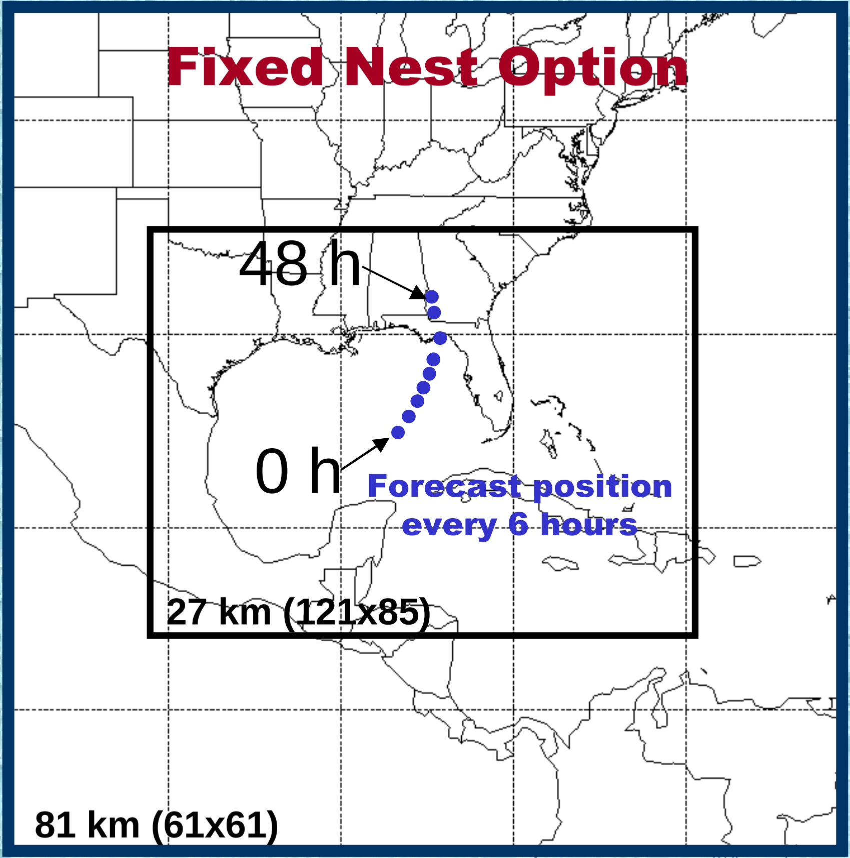
**Valid Time: 0000 UTC 1 July 1999**

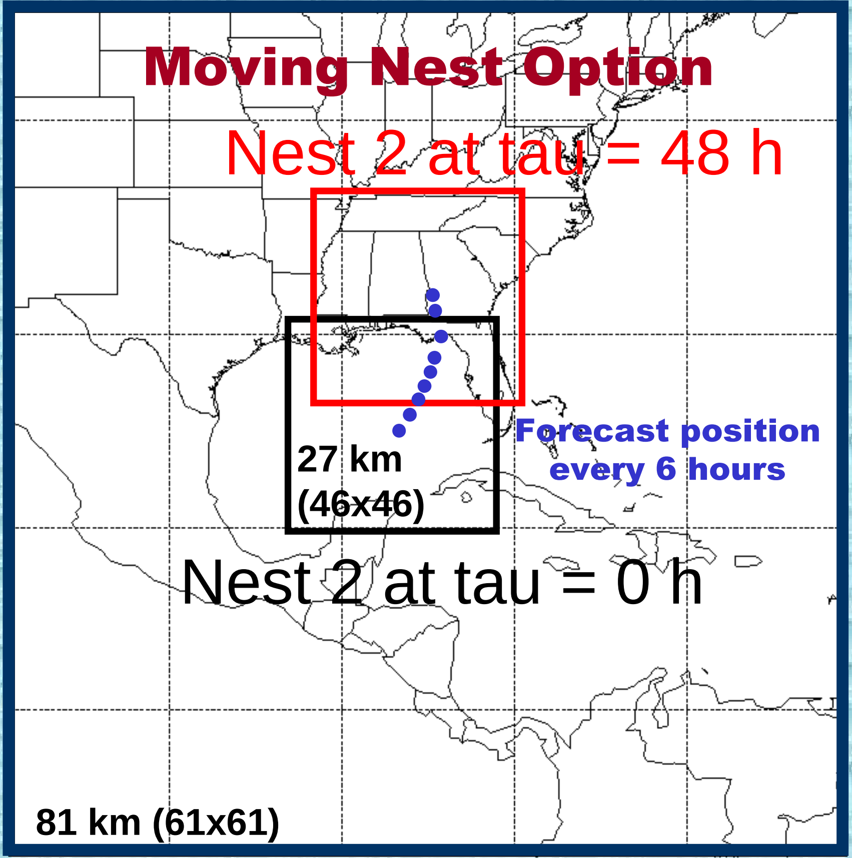
**NCODA: NRL Coastal Ocean Data Assimilation System**



# COAMPS MPI Moving Nests

**Hurricane Gordon: 00Z September 17- 00Z September 19, 2000**



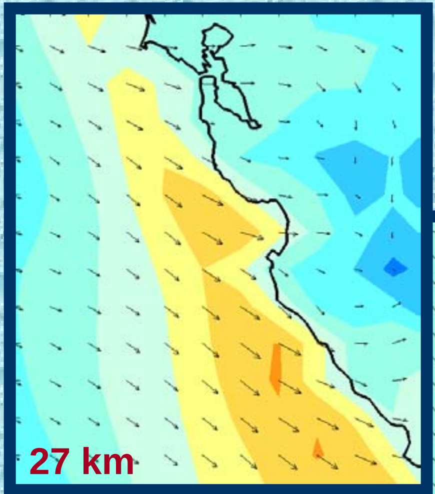

## Results

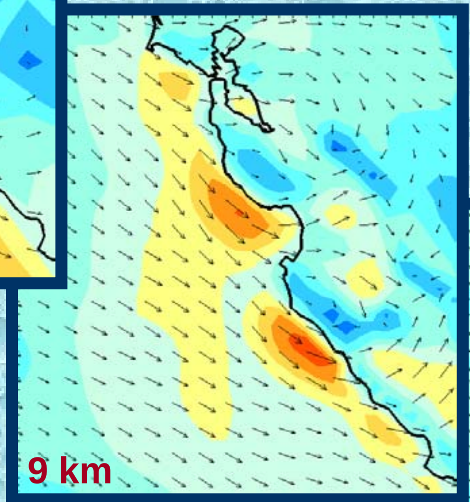
- Identical Track Predictions for Fixed and Moving Nests
- Moving Nest Option: 2.7x Faster

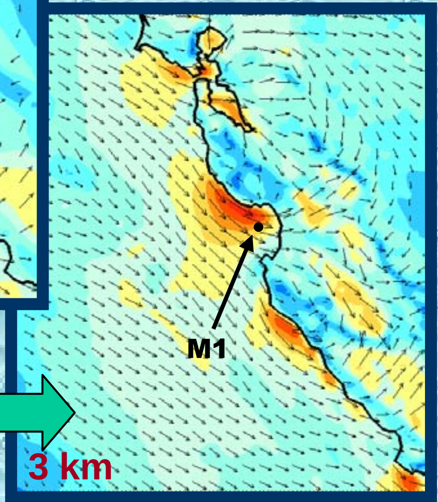
# COAMPS Coupled Studies

## Adaptive Ocean Sampling Network II (AOSN-II)

## Horizontal Resolution Sensitivity/Wind Stress Validation



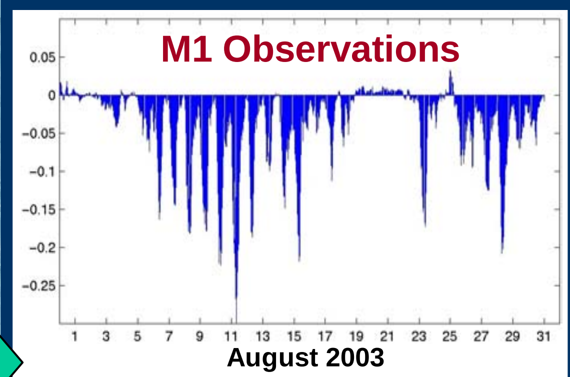



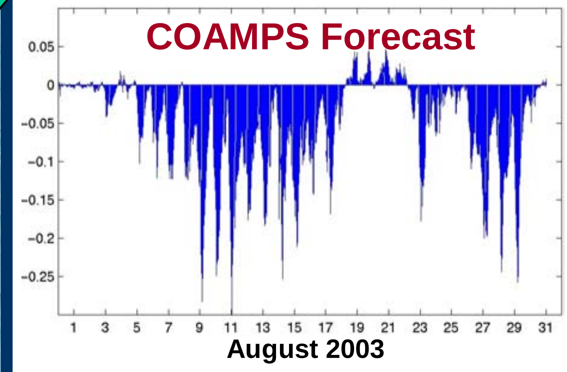

The leftmost 3 boxes show COAMPS wind speed (color) and direction (arrows) for 27, 9, and 3 km grids

**Representation of Coastal Jets, Wind Stress Curl, and Coastal Shear Zones Improved using Higher Resolution Grid**


**COAMPS 3 km Forecast Surface Stress Compares Favorably to Observed Stress at M1 Buoy**

Graphs on right show observed (upper) and COAMPS (lower) Surface Stress



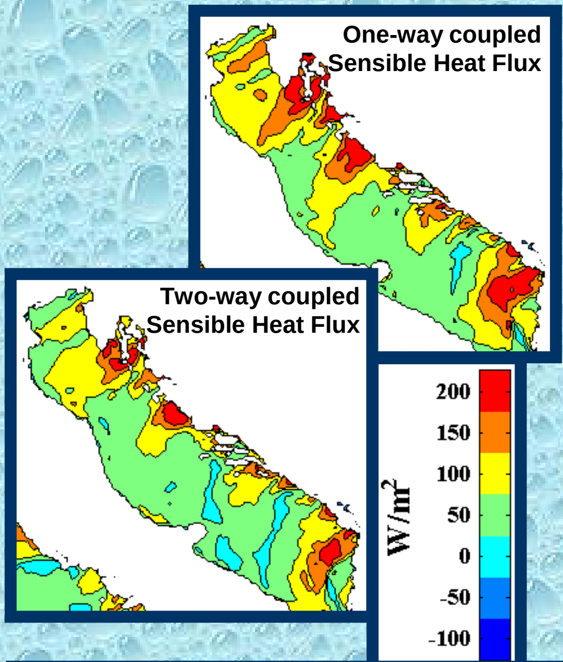

**Ocean Modeling Has Shown:**

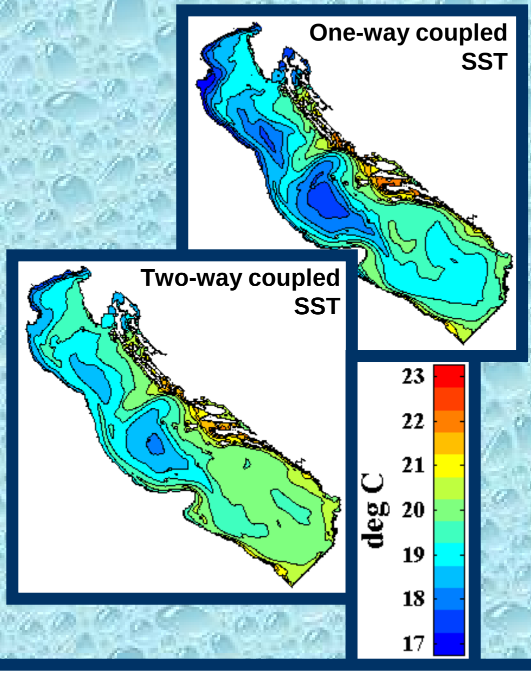
1. *Improved representation of the wind stress curl using the 3 km grid at the coast leads to improved representation of upwelling*
2. *Necessary to use native, unfiltered fields to force ocean models*
3. *Ocean model can be used as metric for atmospheric model validation*

# Two-Way Coupling

## Air-Sea Interaction in the Adriatic Sea

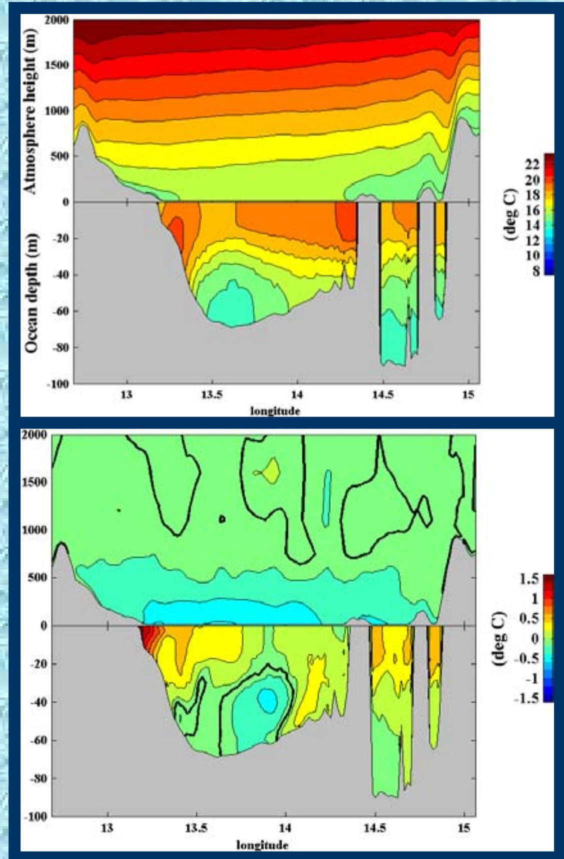
### 30 day means: 23 Sept – 23 Oct 2002




**Two-way coupling exhibits smaller sensible heat fluxes (left), presumably from mutual adjustment in atmosphere and ocean mixed layers. As a result, NCOM SSTs (right) from the two-way coupled system are slightly warmer than those from the one-way coupled system.**

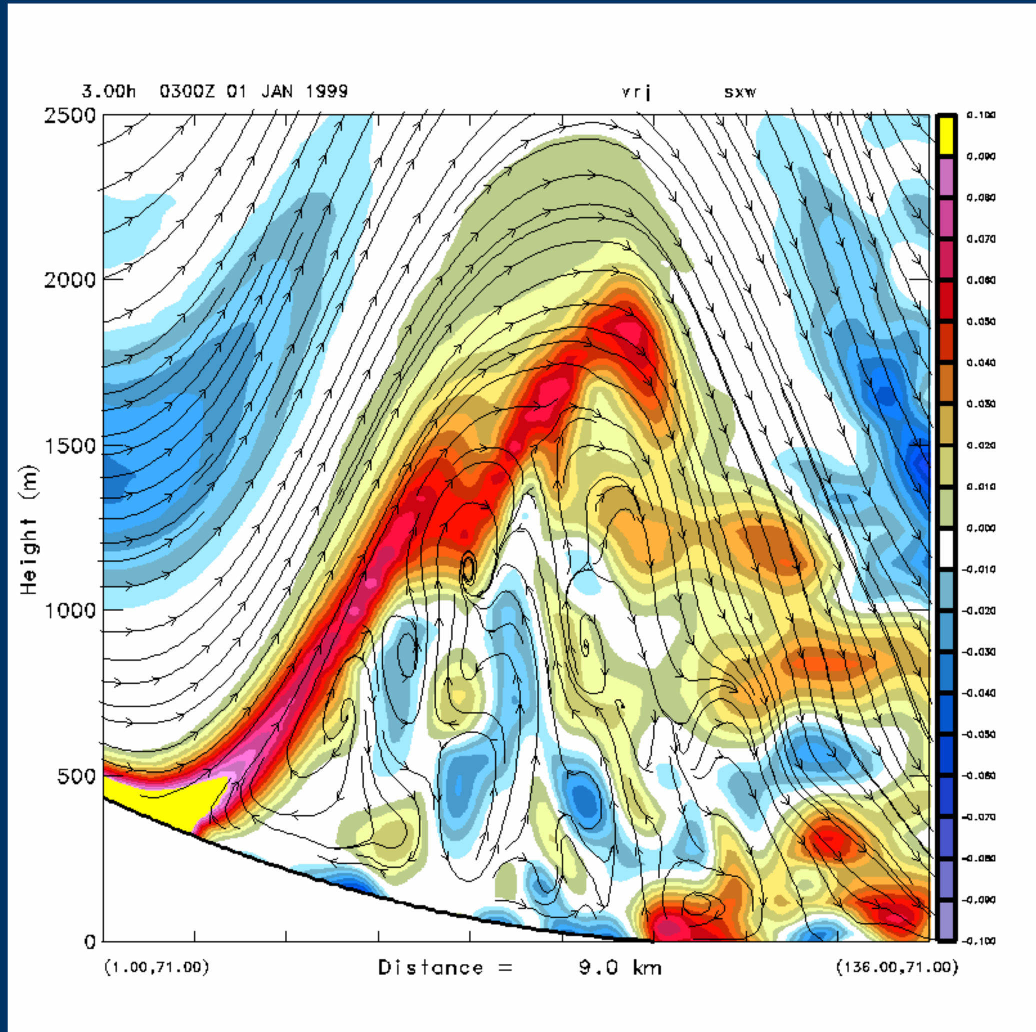
***Lowest near-surface wind and SST RMS and Bias Errors using Two-way Coupling***




**Mean Potential Temperature for Two-way coupling (upper) and [Two-way] - [One-way] differences (lower), showing colder atmosphere mixed layer and warmer ocean mixed layer with two-way coupling.**

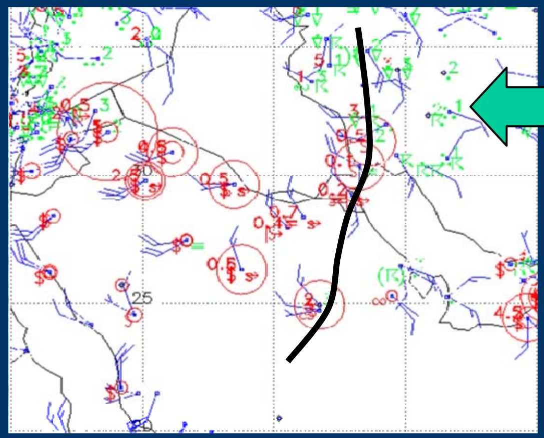
# Mountain-Wave Dynamics

**Rotor: Intense Horizontal Vortex Downstream From a Mountain Ridge**
**Animation of COAMPS Y-Vorticity ($s^{-1}$) and Streamlines (Grid Spacing=67 m)**

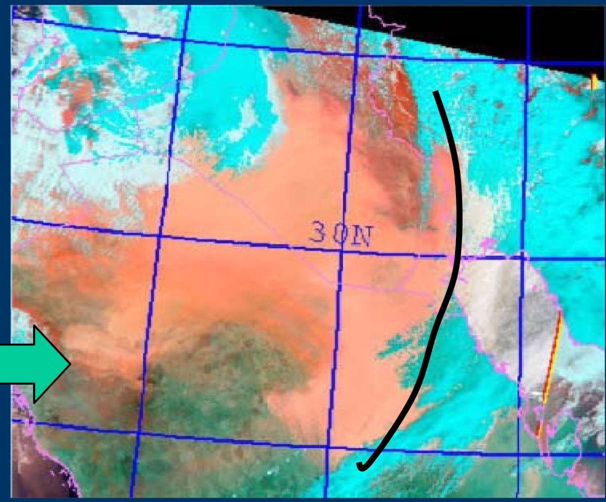



0.10
0.05
0.00
-0.05
-0.10
**Relative Vorticity (1/s)**

# COAMPS™ Dust Forecasting for Operation Iraqi Freedom



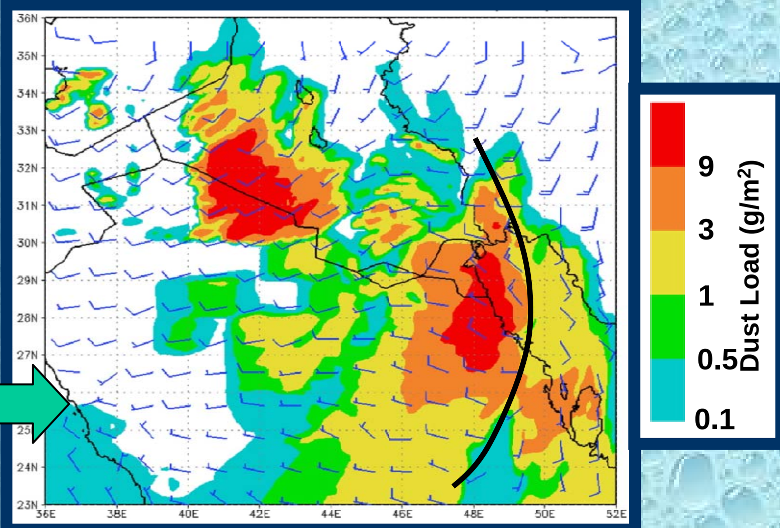
Observed surface dust reports (red) at 0600Z 3/26/2003



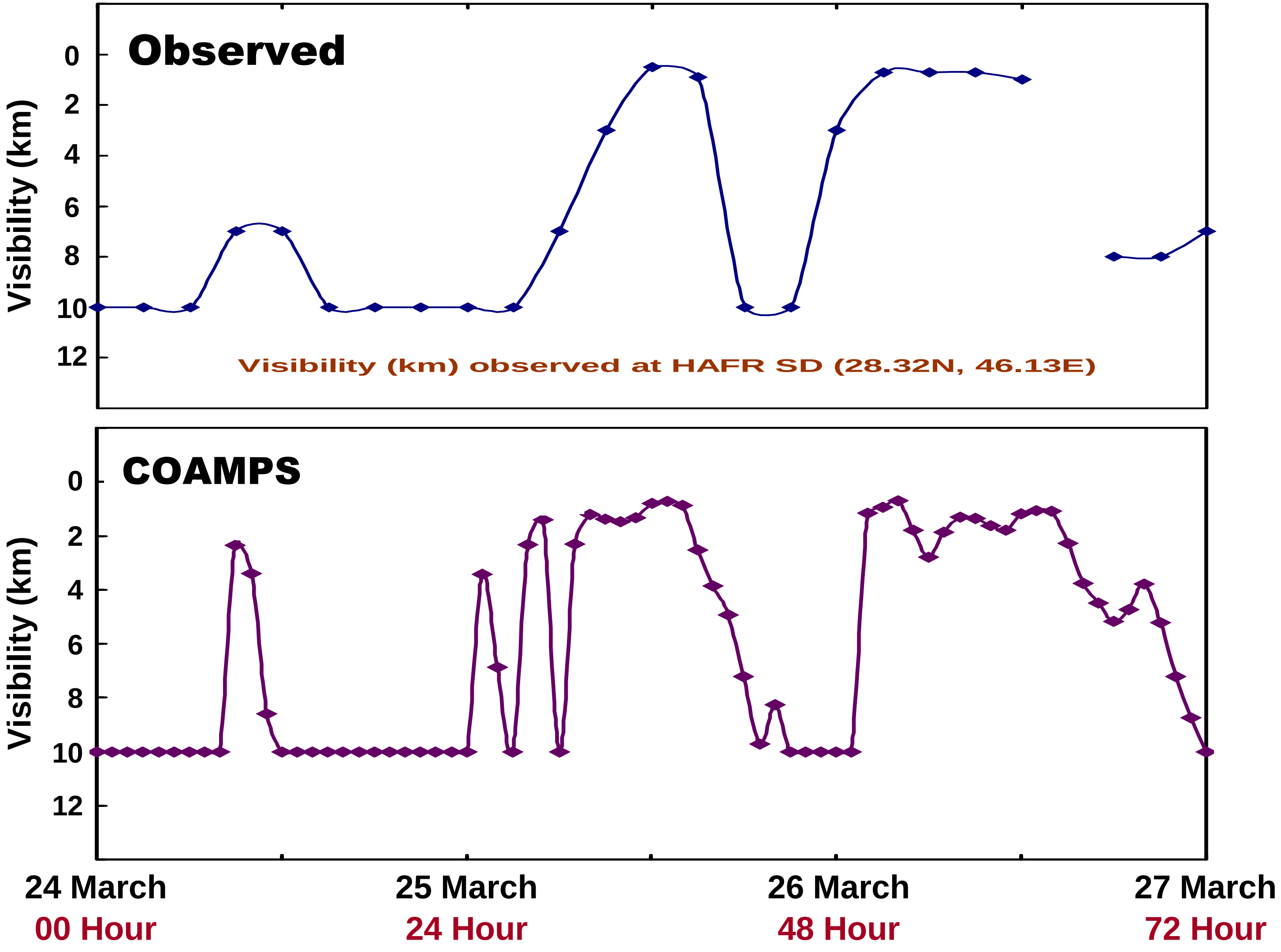

Terra-MODIS at 0745Z 03/26/2003 Pink: Possible dust

**At the beginning of OIF, a strong sand storm occurred on 26-27 March 2003, which grounded aircraft and affected military operations**


COAMPS (9 km) 56 hour forecast dust load valid at 0800Z 03/26/03



# Visibility Comparison During OIF at Hafir Al Batin, Saudi Arabia

# NWP in the U. S. Navy

## Future

## Global Modeling

| Year | Computer | GFLOPS | Model | Data Assimilation |
|---|---|---|---|---|
| 2003 | SGI: 512/128/256/256-p | 2600 | NOGAPS | NAVDAS |
| 2004 | IBM: 288-p added | 4400 | | Direct Assimilation of AMSU-A |
| 2005 | | | Increased number of vertical levels | Predictability/Targeted Observations |
| 2006 | | 13200 | NAAPS; Semi-Lagrangian NOGAPS | Assimilation of additional sensors |
| 2007 | | | Upgrade to Ensembles | |
| 2008 | | | Upgraded Physics | |
| 2009 | | | 15km/60 | |
| 2010 | | 30000 | Advanced Numerical Techniques | NAVDAS-AR |

## Mesoscale Modeling

| Year | Computer | GFLOPS | Model | Data Assimilation |
|---|---|---|---|---|
| 2003 | SGI: 512/128/256/256-p | 2600 | COAMPS | Multivariate Optimum Interpolation |
| 2004 | IBM: 288-p added | 4400 | Aerosols | NAVDAS |
| 2005 | | | Urban Effects | Assimilation of additional sensors |
| 2006 | | 13200 | Air-Ocean Coupling/ESMF/WRF | |
| 2007 | | | Ensembles | Cloud Assimilation |
| 2008 | | | 9/3/1 km/80L | |
| 2009 | | | | |
| 2010 | | 30000 | New Dynamic Core | NAVDAS-AR |

# NAVDAS-AR

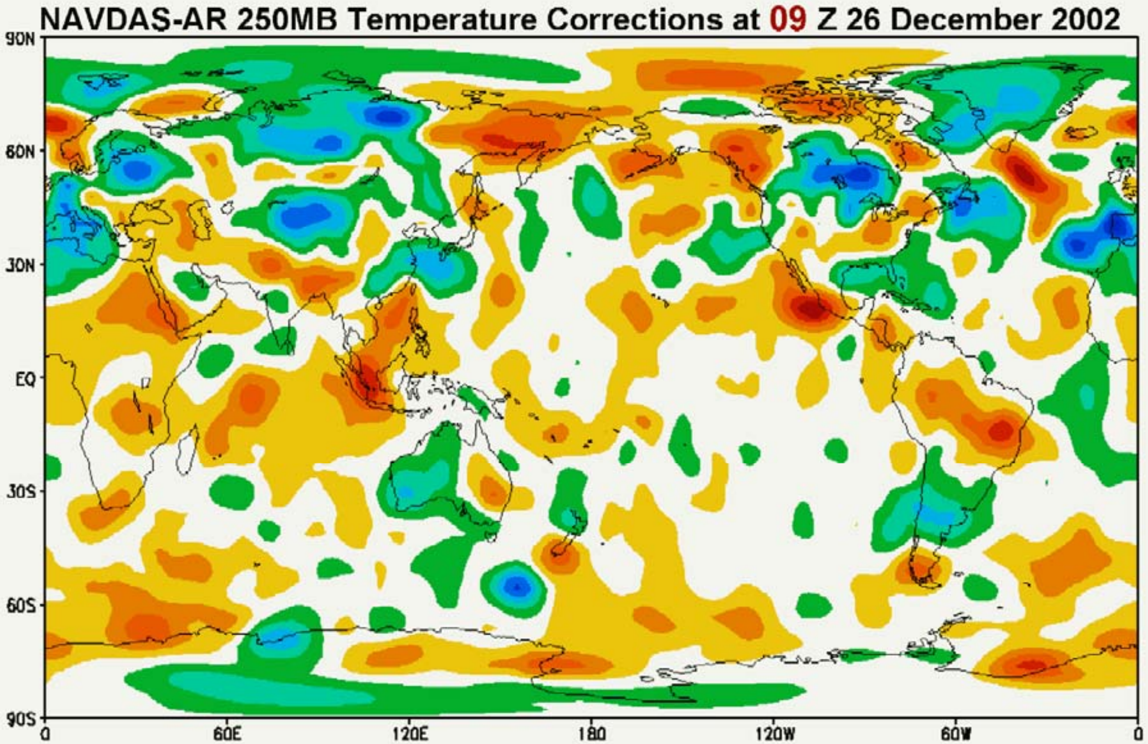
## NAVDAS-Accelerated Representer

- **Natural 4-dimensional extension of NAVDAS** (Xu and Daley, 2002) **built on observation-space algorithm (representer method)**
- **Minimizes a generalized cost function that measures the errors in the background initial condition, in the prediction model, in the observation measurements, and in the observation operators**
- **Equivalent to solving a coupled nonlinear Euler-Lagrange system** (Xu and Rosmond, 2004)
  - Nonlinearity is dealt with through an iterative algorithm – the outer loop strategy
  - Linearized Euler-Lagrange system is decoupled using representer method
  - Resolutions of the outer and inner loops are currently T239L30 and T79L30, respectively
- **Computational cost of 2 outer loops in NAVDAS-AR is currently about 10 times of that of NAVDAS**
- **Perfect model assumption is currently used as a special case of model error representation** (no model error covariance included in cost function)

# NAVDAS-AR Assimilation

**Outer Loop:** T239L30**, Inner Loop:** T79L30

400,000 operational observations

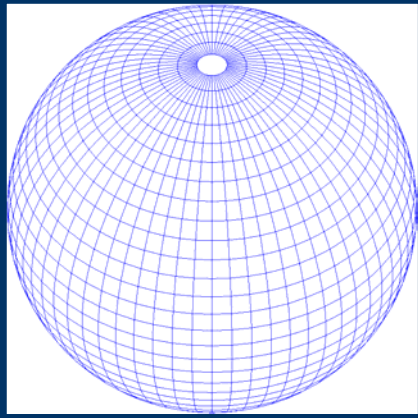



- **Operational observations are all assimilated at the times of observations in NAVDAS-AR**
- **NAVDAS-AR uses the prediction system to constrain the analysis**

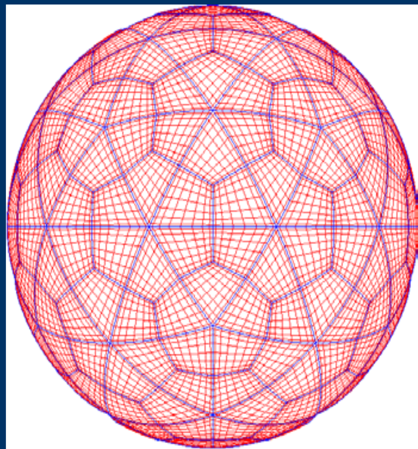
# Next-Generation NOGAPS

**Testing skill and efficiency of Spectral Semi-Lagrangian and Icosahedral grid formulations against the current Spectral Eulerian formulation**

- **Current Model:**
  - **Spectral/Eulerian**
  - Operational (T239L30, ~55km)
  - Lat/Lon grid for physics
  - Problems with positive definite quantities
  - Requires small time steps
- **Short-Term:**
  - **Spectral/Semi-Lagrangian/Semi-Implicit**
  - Improved efficiency: Much larger time steps
  - Positive definite advection
  - Lat/Lon grid for physics
  - Thinned grid near the poles: Increased efficiency
  - New formulation of hydrostatic equation: Higher model top
- **Long-Term:**
  - **Icosahedral Grid**
  - Improved efficiency
  - Positive definite advection
  - Can use spectral elements or Semi-Lagrangian advection
  - Potential for unified global/mesoscale model



Lat/Lon Grid



Icosahedral Grid

# Future of COAMPS

- **Mesoscale Modeling 2005-2007:**
  - **Coupled to ocean model** (NCOM) **using ESMF**
  - **Movable-nest for battle-group and tropical cyclone applications**
  - **Mesoscale ensembles**
  - **Integrated into WRF framework** (Interchangeable physics suites)
  - **COAMPS adjoint**
- **Mesoscale Modeling 2008+:**
  - **New formulation will require ~50X increase in computations:**
    - Horizontal resolution: 27/9/3 km to 27/9/3/1 km (moving grids, explicit convection)
    - Vertical resolution: ≥ 60 levels
    - Analysis of non-conventional observations, (e.g., radar, clouds, refractivity)
    - Multi-component aerosol modeling, interactive w/radiation and microphysics
    - Urban applications
    - Exploration of hybrid coordinates for representing vertical surfaces
  - **Coupled mesoscale ensemble prediction**
  - **NAVDAS-AR**

# NWP in the U. S. Navy

## Concluding Remarks

*Navy has made significant upgrades to NWP capabilities*

- **Processing Power:**
  - **1974:** 0.003 GFLOPS
  - **2004:** 4,400 GFLOPS
  - **2010:** 30,000 GFLOPS
- **Data Assimilation:**
  - **1974:** Fields-by-Information Blending
  - **2004:** NAVDAS
  - **2010:** NAVDAS-AR
- **Global Modeling:**
  - **1974:** Northern Hemisphere PE model (381km/L6)
  - **2004:** NOGAPS (T239/L30), NAAPS (Aerosols)
  - **2010:** ~12km, Semi-Lagrangian, Improved Ensembles, Aerosols
- **Mesoscale Modeling:**
  - **1974:** Cold Starts
  - **2004:** Nonhydrostatic, Moving Multi-Nests, 6 kmL30, Aerosols
  - **2010:** ~1 km, 2-way coupling, Urban Applications

# NWP in the U. S. Navy

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ECMWF
25-29 October 2004

## Outline

- **Background: Data Assimilation and Modeling Systems**
- **History of Modeling in the Navy**
- **Current Status**
- **Future Plans**
- **Concluding Remarks**