In Situ and Satellite Sea Surface Temperature (SST) Analyses

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1. Project Summary

The purposes of this project are: 1) to improve the climate-scale sea surface temperature (SST) analyses produced at NOAA for climate research and monitoring as well as applications to societal benefits; and 2) to monitor and report the performance of the global ocean SST observing system in terms of a Government Performance and Results Act (GPRA) Performance Measure, for an optimum integration of the in-situ and satellite observation systems for climate scale SST. This project supports the NOAA's Next Generation Strategy Plan (NGSP) goal of "Climate Adaptation & Mitigation" through sufficient climate observation and analysis. This project directly serves the COD's Program Deliverables in: 1) To identify climate variability through surface marine observations including SST and sea surface winds; and 2) To identify changes in forcing functions through the air-sea exchange processes. Our SST analyses are available via http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php and http://www.ncdc.noaa.gov/ersst.

One of the important goals of the Sustained Ocean Observing System for Climate is to improve the SST accuracy over the global ocean for climate change monitoring and assessment. Because of the dense spatial coverage of satellite data, in situ data tends to be overwhelmed by satellite data. Thus, the most important role of the in situ data in the analysis is to correct large-scale satellite biases. Simulations with different buoy densities showed the need for at least two buoys on a 10° spatial grid to reduce a satellite bias of 2°C to not exceeding 0.5°C (minimum requirement; citations in Zhang et al 2009). Using this criterion, regions were identified where additional buoys are needed, and a metric was designed to measure the adequacy of the present observing system as a GPRA performance measure. The work presented here follows the Global Climate Observing System (GCOS) Ten Climate Monitoring Principles.

NOAA has combined the in-situ and satellite SST observations into gridded SST products. The NOAA's Optimum Interpolation (OI) SST analysis products (often also referred to as Reynolds SST Analyses) are among the most utilized SST products (more than 3000 citations). Currently two operational versions of the OISSTs are maintained at NOAA/NCDC; both of them are bias-corrected by in-situ observations, and with spatial and temporal resolutions of ¼-degrees and daily, respectively. 1) The AVHRR-only OISST uses infrared satellite data from the Advanced

Very High Resolution Radiometer (AVHRR). The dataset spans ~30 years (from September 1981 to the present). Among many other applications, it has been used for intercomparison studies and as a first guess for retrieval algorithms for past and current sensors (e.g., MODIS, TRMM, VIIRS, PATHFINDER, etc). 2) The AMSR+AVHRR OISST uses AVHRR and microwave satellite data from the Advanced Microwave Scanning Radiometer (AMSR-E), which has the advantage of nearly all-weather coverage, and therefore is better for forecasting and hurricane tracking. The product is available for the lifetime of the AMSR-E instrument (from June 2002 to Oct. 6, 2011). Improvements are being made to the above two operational products. In particular, a replacement microwave instrument for AMSR-E needs to be investigated if this version of time series is to continue. The data are available at http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php.

Additional work has been carried out to improve the historic Extended Reconstruction SST (ERSST) analysis which begins in 1854. This analysis uses in-situ data only, and is computed monthly on a 2° spatial grid. The reconstructions are produced from a low frequency (or decadal-scale component) and from a residual high-frequency component. The high frequency analysis was performed by fitting the observed high frequency anomalies to a set of large-scale spatial-covariance modes. A merged surface temperature product uses both SSTs and land surface temperatures (LSTs), and is produced monthly on a 5° grid beginning in 1880. Both the SST-only and merged products are important in monitoring long-term changes in climate and are available at http://www.ncdc.noaa.gov/ersst/ and http://www.ncdc.noaa.gov/cmb-faq/anomalies.php, respectively.

2. Scientific and Observing System Accomplishments

Accomplishment Highlights: In FY2011, ***the operational OISST continued to be available*** to the scientific community on schedule, with 1-day latency for the near-real time product, and 15-day latency for the final version when more and better in situ and satellite data became available. ***Improvements include*** the replacement of NOAA-18 with NOAA-19 as the source of AVHRR data.

Two new OISST products have been under development in FY11: 1) A higher resolution (~ 5km) OISST, taking the advantages of complementary natures of the AVHRR (better resolution) and microwave (better data coverage) SST observations; and 2) A nighttime AVHRR OI SST, to minimize potential diurnal biases for climate studies.

The error estimate of the ERSST v3b has been revised. The operational ERSST v3b has been maintained and updated at the 3rd day of every month (http://www.ncdc.noaa.gov/ersst), with a monitoring webpage added. Under development is the monthly ERSST v4.0.0 using ICOADS Release 2.5 and NCEP GTS from 1854 to present.

On quarterly basis, ***we have produced the seasonal maps showing where drifting buoy are adequate and where additional drifting buoys need to be deployed, together with the SST GPRA performance metric.*** These have been sent to AOML and CPO/OCO and reported to NOAA and upward as NOAA's Balanced Scorecard report.

This project directly serves the COD's Program Deliverables in: 1) To identify climate variability through surface marine observations including SST and sea surface winds; and 2) To identify changes in forcing functions through the air-sea exchange processes.

Specific Deliverables:

- ***High Resolution OI Blended SST Analysis:*** A two-stage SST analysis procedure has been developed with a high-resolution analysis built on top of a low-resolution analysis. Reynolds, et al. (2007) developed two lower-resolution SST analysis products using optimum interpolation (OI). The analyses have a spatial grid resolution of 0.25° and temporal resolution of one day. One product uses Advanced Very High Resolution Radiometer (AVHRR) satellite SST data. The other uses Advanced Microwave Scanning Radiometer (AMSR) and AVHRR satellite SST data. Both products also use in situ data from ships and buoys and include a large-scale adjustment of satellite biases with respect to the in situ data. For the present effort, the AMSR and AVHRR product would be used as the low-resolution analysis, because the AMSR has the superior coverage compared to AVHRR alone due to the use of microwave data.

  The second step produces a high-resolution analysis on a 0.04395° (~1/23° or 4.9 km at the equator) grid that uses the lightly damped low-resolution analysis and a strongly damped previous high-resolution analysis as a first guess. This high-resolution analysis step has been developed. However, several problems became evident especially at boundaries between the high- and low-resolutions. To better understand how to correct these problems, an extended effort has been undertaken to show how space-time distributions of satellite SST data were impacted by data sampling. The procedure used to demonstrate this impact began with daily complete SST fields from a high-resolution global model, which were considered to be the "true" SST. Both low resolution (~50 km) and high resolution (~5 km) pseudo data were derived from the model to represent microwave and infrared satellite data, respectively. These fields were then treated as data and subsampled based on actual satellite SST data distributions from one microwave instrument and from one infrared instrument. The full and subsampled SST data fields were then analyzed and compared to assess the influence of missing low-resolution and high-resolution data.

  The results also showed that the spectral variance of a high-resolution analysis using the reduced or subsampled data at high wavenumbers were as large as or larger than the original input data (Fig. 1). This result indicates that the analysis with reduced data added high-resolution noise when filling in missing data. Cross-spectral analysis with respect to the input data confirmed that the high resolution analysis produced increasing noise as the coverage decreased. These results also showed that high resolution data coverage in the Gulf Stream was not likely in January and only possible about half the time in July. The Sargasso Sea had high resolution coverage during much of January and most of July due to reduced cloud coverage compared to the Gulf Stream.

  These results entitled "Objective Determination of Feature Resolution in an SST Analysis." were presented at two meetings: the GHRSST Science Team meeting,

Edinburgh, UK, 21-25 June 2011, and the NASA SST Science Team Meeting, Miami, FL, 2-4 November, 2011. An extended abstract from the GHRSST meeting is attached and a draft paper for eventual per-reviewed publication is being prepared.

During the coming year the work on the objective determination of feature resolution will be continued. Users may expect that if high resolution data are not available that analyses will not show high resolution features. Unfortunately, this assumption is wrong. High resolution analyses show high resolution features with and without high resolution data, but in the latter case the high resolution features are just noise. The SST ocean model data from the objective determination study will be used to reduce high-resolution noise in the two-stage OI. This effort will include examining the damping of high-resolution features from previous time-periods and by not performing the high-resolution step when the fractional coverage of high-resolution ocean grid boxes with data is low compared to the total. In the coming year, the high resolution analysis step in the two-stage OI will be finalized. The final tunings using the simulated data should be completed, and then to complete the two-staged analysis, and make the analysis available to users along with documentation.

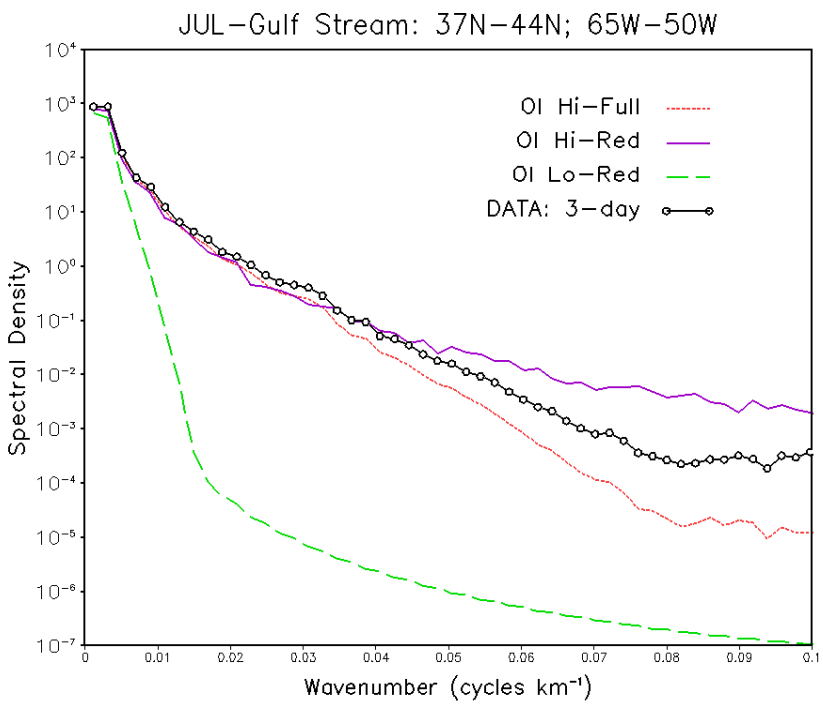

Fig. 1 Auto-spectra of the OI analyses and data for July 1993 for the Gulf Stream. 'OI Hi-Full' is the high resolution OI with the full data. 'OI Hi-Red' is the high resolution OI with the reduced data. 'OI Lo-Red' is the low resolution OI with the reduced data. 'DATA: 3-day' is the full high resolution 3-day data. The horizontal axis shows the wavenumber in cycles km-1.The vertical axis shows the spectral density (oC2 per cycle km-1).

- ***Nighttime-only OISST:*** The current operational OISSTs combine daytime and nighttime observations. The daytime observations contain diurnal warming, thus increasing variability in the SST analysis. To minimize this effect, a nighttime only version of the OISST has been in development, using nighttime-only in-situ and AVHRR data.

Preliminary work has been presented at the 2011 GHRSST Science Team meeting. One-year nighttime-only analysis was compared to the daytime-only SST analyses as well as the current operational OISST products (using both daytime and nighttime observations). The nighttime SST time series will be provided to satellite SST algorithm developers to see if they are useful as a reference field and/or a first-guess field.

- ***Reprocessing of the ERSST:*** In FY2011, the operational ERSST code has been revised to be more machine independent. The error estimates of ERSST v3b has been revised, including improvements in the estimations of high frequency (HF) sampling error variance, variance deviated from climatology or 15-yr running mean, separation of land and ocean error, and bias error between U.K. Met Office (UKMO) and Smith and Reynolds 2002 (SR2002). These error revisions have been implemented in the operational ERSST products.

  The operational ERSST v3b has been maintained and updated at the 3rd day of every month (http://www.ncdc.noaa.gov/ersst). ERSST data are available at ftp://ftp.ncdc.noaa.gov/pub/data/cmb/ersst/v3b. To ensure correct and on-time production, a monitoring web page (http://bhuang.dev.ncdc.noaa.gov/sst.png.shtml) is designed to display the input data numbers and spatial distributions (buoy, ship, and ice observations), major indices (NINO, PDO, regional and global averages), and their error estimate. These enable us to diagnose the problem if production goes wrong. Also, the ERSST web site has been revised substantially.

  For development, monthly ERSST v4.0.0 has been generated, using ICOADS Release 2.5 and NCEP GTS from 1854 to present. The data has been compared with ERSST v3b and other products and being updated monthly; description can be found in Vose et al (2011; submitted to BAMS).

  Currently under development is a new bias correction algorithm to correct historic SST observations in ICOADS Release 2.5.

  A manuscript has been submitted to J. Climate for publication (Huang et al 2012). The analysis of ERSST and global land surface temperature is motivated by “to identify significant patterns of climate variability and change”. The EOF analysis successfully identified the modes for global warming trends and ENSO variability at different seasons. Major oceanic variabilities are well defined in the ERSST. The dipole modes were identified between Eurasia and Africa-South Asia in winter and between Eurasia and North America in summer at interannual timescales. The conclusion is that ERSST and the merged Land-Ocean surface temperature (MLOST) are suitable for the climate analysis and monitoring.

- ***Operational Monitoring of the SST GPRA Performance Metric and Buoy-Need Maps:*** On quarterly basis, we have produced the seasonal maps showing where drifting buoy are adequate and where additional drifting buoys need to be deployed, together with the SST GPRA performance metric. These have been sent to AOML and CPO/OCO and reported upward to NOAA, as well as quarterly report to the Department of Commerce as one of

NOAA's Balanced Scorecard. In 2011, the GPRA measure was slightly below the target (errors are slightly above 0.5°C; Fig. 2). This has been attributed to the decreased number of drifting buoys in the ocean (e.g. Fig. 3), partly due to unexpected early death of some drifters. The reason for the early death has been identified and remedies are being made by the buoy manufactures.

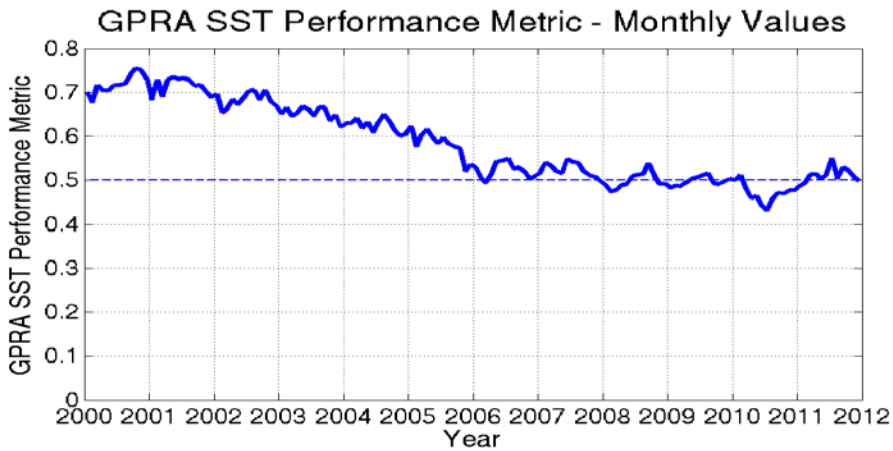

Fig. 2 The GPRA Performance Measure versus time. The dashed line is the target.

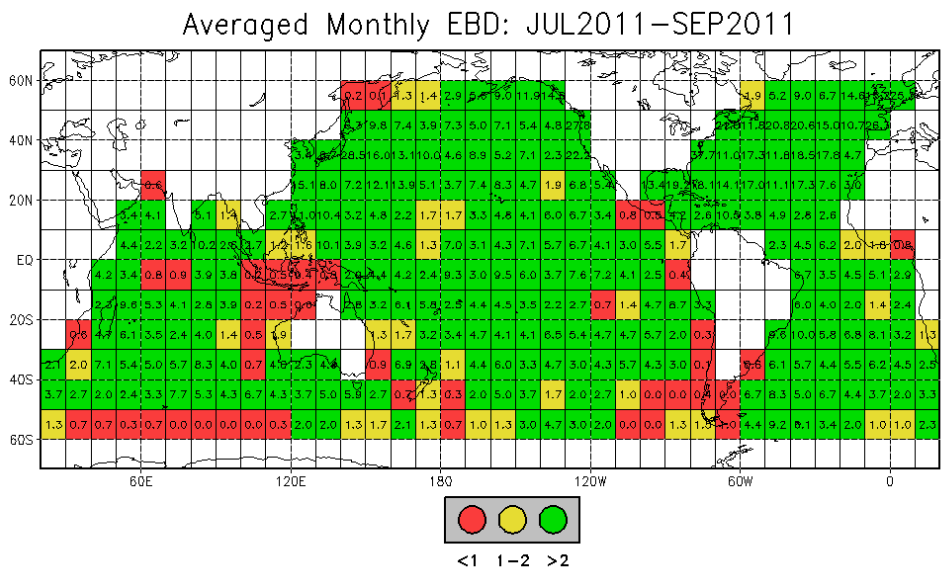

Fig. 3 The Buoy Need Map showing where observations are adequate (green) and where additional buoys are needed (red). Note that for the Quarter of July – Sept 2011, there were eight (8) 10°x10° boxes between 40°S-60°S within which there were no buoys.

2.1. Outreach and Education

Dr. Richard W. Reynolds serves on the WCRP's Ocean Observation Panel of Climate (OOPC) and the Group for High Resolution Surface Temperature (GHRSST) Science Team. Members of both groups consist of well-known national and international scientists. Dr. Reynolds is a well-

respected and published scientist as noted at: http://in-cites.com/papers/RichardReynolds.html. The SST analyses, often referred as the "Reynolds SSTs" or "Optimum Interpolation (OI) SSTs", are widely used for many purposes including hurricane and other weather forecasting, fisheries (through better location of isotherms and the fish that follow them) and for climate prediction and analysis. Dr. Huai-Min Zhang has taken the lead publishing papers on the requirements for buoy SST data to ensure that satellite data are unbiased. He produces seasonal summaries which impact buoy deployments. Dr. Zhang serves on the WCRP SEAFLUX and SURFA (Surface Flux Analysis) Working Groups. Dr. Zhang also worked in the NOAA Budget Office for 3 months, including briefing the SST GPRA metric to NOAA and DOC. Dr. Viva Banzon worked on the ERSST and night-time only OI SST projects, and made numerous presentations at national and international meetings. She is also a member of the GHRSST Science Team.

Results from this project have been reported in national and international meetings, including AMS, AGU, the GHRSST Science Team, NASA SST Science Team, among others. The OISST papers have been among the most citied publications in geosciences internationally (more than 3000 citations). Non-inclusive registered users are roughly 300 for the OISSTs, and about 100 for the ERSST.

3. Publications and Reports

3.1. Publications by Principal Investigators

Banzon, V. and R.W. Reynolds, 2011: "Nighttime only SST fields", *XII GHRSST Science Team Meeting*, 29 June 29 – 1 July 2011, Edinburgh, Scotland.

Dash, P. , A. Ignatov, M. Martin, C. Donlon, B. Brasnett, R. W. Reynolds, V. Banzon, H. Beggs, J.-F. Cayula, Y. Chao,R. Grumbine, E. Maturi, A. Harris, J. Mittaz, J. Sapper, T. M. Chin, J, Vazquez, E. M. Armstrong, C. Gentemann, J. Cummings, J. P. Piolle, E. Autret, J. Roberts-Jones, S. Ishizaki, J. Hoyer, and D. Poulter. Group for High resolution SST (GHRSST Analysis Fields Inter-Comparisons Part 2. Near real time web-based Level 4 SST Quality Monitor (L4-SQAM). *Deep Sea Research II* (Special Issue on Satellite Oceanography and Climate) (submitted).

Fairall, C. W., H.-M. Zhang, G. Peng, S. Stevens, A. Brown, and D. Majewski, 2011: Surface Flux Analysis (SURFA) – Update on recent activities. *The 27th Session of the WCRP-JSC/CAS Working Group on Numerical Experimentation (WGNE)*, 17 – 21 October 2011, Boulder, CO, USA.

Huang, B., E. Freeman, J. Lawrimore, Chunying Liu, R. W. Reynolds, and D. Wuertz, 2012: Climate variabilities in merged land-ocean surface temperature (MLOST). *J. Climate*, (submitted).

Liu, C., R.W. Reynolds, T. Smith, and V. F. Banzon, 2011: Comparison of the NCDC Sea Surface Temperature Datasets: ERSST and OISST, *The 91st American Meteorological Society Annual Meeting*, 23 – 27 January 2011, Seattle, Washington, USA.

Liu, C., R.W. Reynolds, and A. Hall, 2011:The Optimum Interpolation Sea Surface Temperature(OISST) From Research to Operations, *2011 AGU Fall Meeting*, 5 – 9 December 2011, San Francisco, California, USA.

Martin, M, P. Dash, A. Ignatov, V. Banzon, H. Beggs, B. Brasnett, J.-F. Cayula, J. Cummings, C. Donlon, C. Gentemann, R. Grumbine, S. Ishizaki, E. Maturi, R. Reynolds, J. Roberts-Jones. Group for High resolution SST (GHRSST Analysis Fields Inter-Comparisons Part 1. A GHRSST Multi-Product Ensemble (GMPE). *Deep Sea Research II* (Special Issue on Satellite Oceanography and Climate) (submitted).

Peng, G., H.-M. Zhang, H.P. Frank, J.-R. Bidlot, M. Higaki, S. Stevens, and W.R. Hankins, 2012: Evaluation of remotely-sensed and model surface wind forecast and reanalysis products with OceanSITES buoy measurements. *Weather and Forecasting* (submitted).

Peng, G., H.-M. Zhang, H.P. Frank, J. Bidlot, M. Higaki, and W. Hankins, 2011: A comparison of various Equatorial Pacific surface wind products, *Proc. IGARSS 2011*, 2049 – 2052, 24 – 29 July, 2011, Vancouver, Canada.

Reynolds, R.W., and D.B. Chelton, 2011: Objective Determination of Feature Resolution in an SST Analysis. XII GHRSST Science Team Meeting, Edinburgh, Scotland, 29 June 29 – 1 July 2011.

Vose, R. S., D. Arndt, V. F. Banzon, D. R. Easterling, B. Gleason, B. Huang, E. Kearns, J. H. Lawrimore, M. J. Menne, T. C. Peterson, C. N. Williams, D. L. Wuertz, 2011: NOAA's Merged land-ocean surface temperature analysis. *Bull. Amer. Meteor. Soc.*, (submitted).

Woodruff, S., S. Worley, S. Lubker, Z. Ji, E. Freeman, D. Berry, P. Brohan, E. Kent, D. Reynolds, S. Smith, C. Wilkinson, 2011: ICOADS Release 2.5: Extensions and Enhancements to the Surface Marine Meteorological Archive. *International Journal of Climatology,* 31, 951-967, (DOI: 10.1002/joc.2103).

3.2. Other Relevant Publications

The publications for SST products discussed above have been reference extensively. For example, a web search on the "Microsoft Academic Search" (http://65.54.113.26/Search?query=richard%20w%20reynolds) showed that the original OISST paper (Reynolds and Smith 1994) was cited nearly 1300 times! The second OISST paper (Reynolds et al 2002) was cited nearly 1000 times. The two in-situ based ERSST papers (Smith et al 1996 and 2004) were cited about 733 times.

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Reynolds, R.W., T.M. Smith, 1994: Improved Global Sea Surface Temperature Analyses Using Optimum Interpolation. *J. Climate*, **7** (no. 6), DOI: 10.1175/1520-0442(1994)007.

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Smith, T.M., R. W. Reynolds, R.E. Livezey, and D.C. Stokes, 1996: Reconstruction of Historical Sea Surface Temperatures Using Empirical Orthogonal Functions. *J. Climate*, **9** (no. 6), 1403-1420.

Smith, T.M., R. W. Reynolds, 2004: Improved Extended Reconstruction of SST (1854–1997). *J. Climate*, **17** (no. 12), DOI: 10.1175/1520-0442(2004)017.

Smith, T. M., and R. W. Reynolds, 2002: Bias Corrections for Historical Sea Surface Temperatures Based on Marine Air Temperatures. *J. Climate*, **15**, 73-87.

Zhang, H.-M., R.W. Reynolds, R. Lumpkin, R. Molinari, K. Arzayus, M. Johnson, T.M. Smith, 2009: An Integrated Global Ocean Observing System for Sea Surface Temperature Using Satellites and In situ Data: Research-to-Operations, *Bull. Amer. Meteorol. Soc.*, **90** (No. 1), 31-38, DOI: 10.1175/2008BAMS2577.1