Sensitivity of Surface Turbulent Fluxes to Errors In Bulk Formula Inputs

– or –

Where We Could Go Seriously Wrong

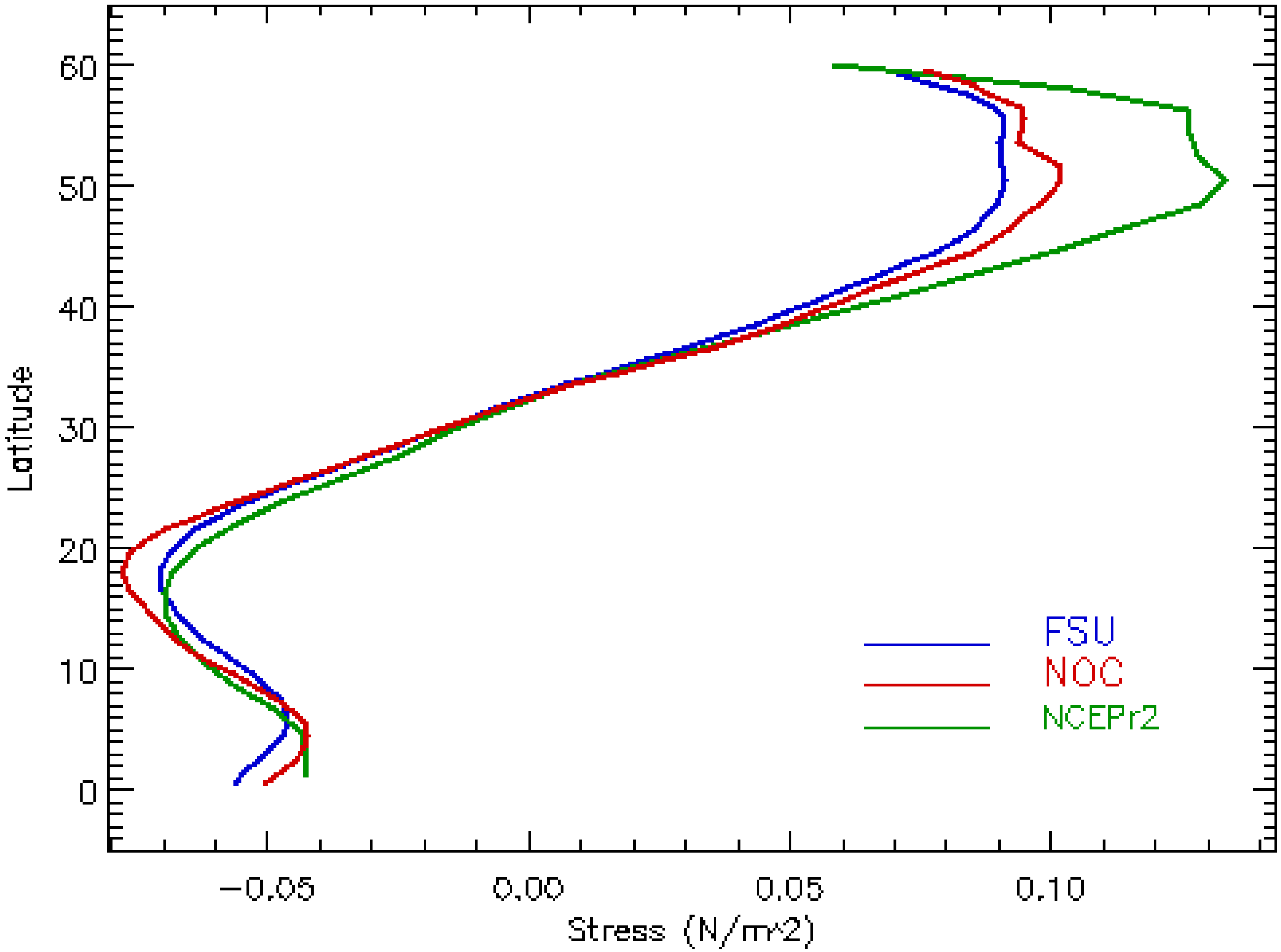
Mark A. Bourassa and Paul J. Hughes

Center for Ocean-Atmospheric Prediction Studies &
Department of Meteorology,
The Florida State University

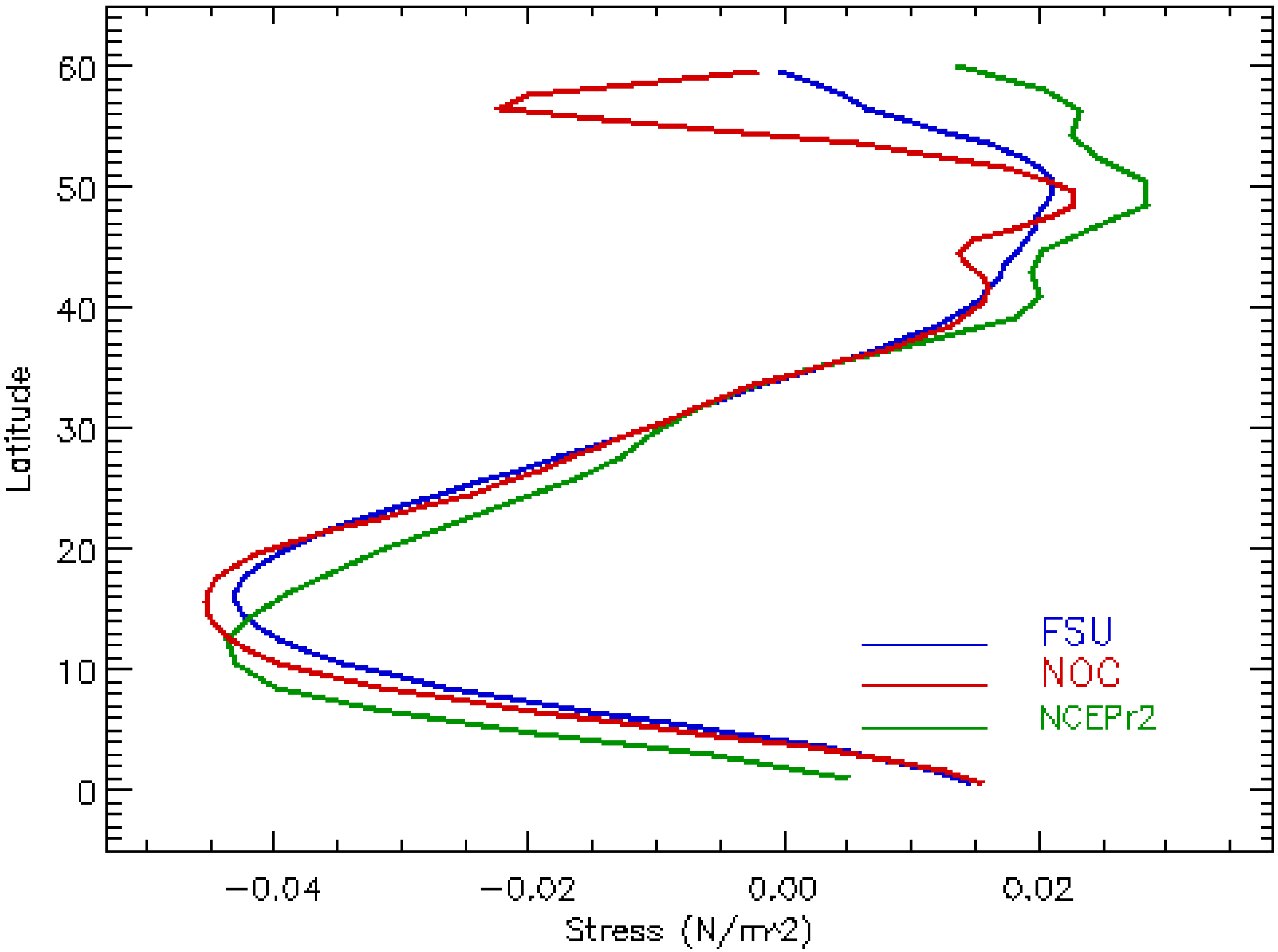
Differences in Forcing Products

- There are large differences in surface forcing products.
- NWP Products
  - Disadvantages:
    - Poor boundary-layer representation
    - Questionable (at best) flux parameterization
  - Advantage: forecasts
- Satellite-based Products
  - Advantages: Great winds and SSTs, and potentially stress
  - Disadvantages:
    - Poor heat fluxes
    - No forecast
- In situ-based Products
  - Advantages: relatively good input to heat fluxes
  - Disadvantages: poor sampling, no forecast

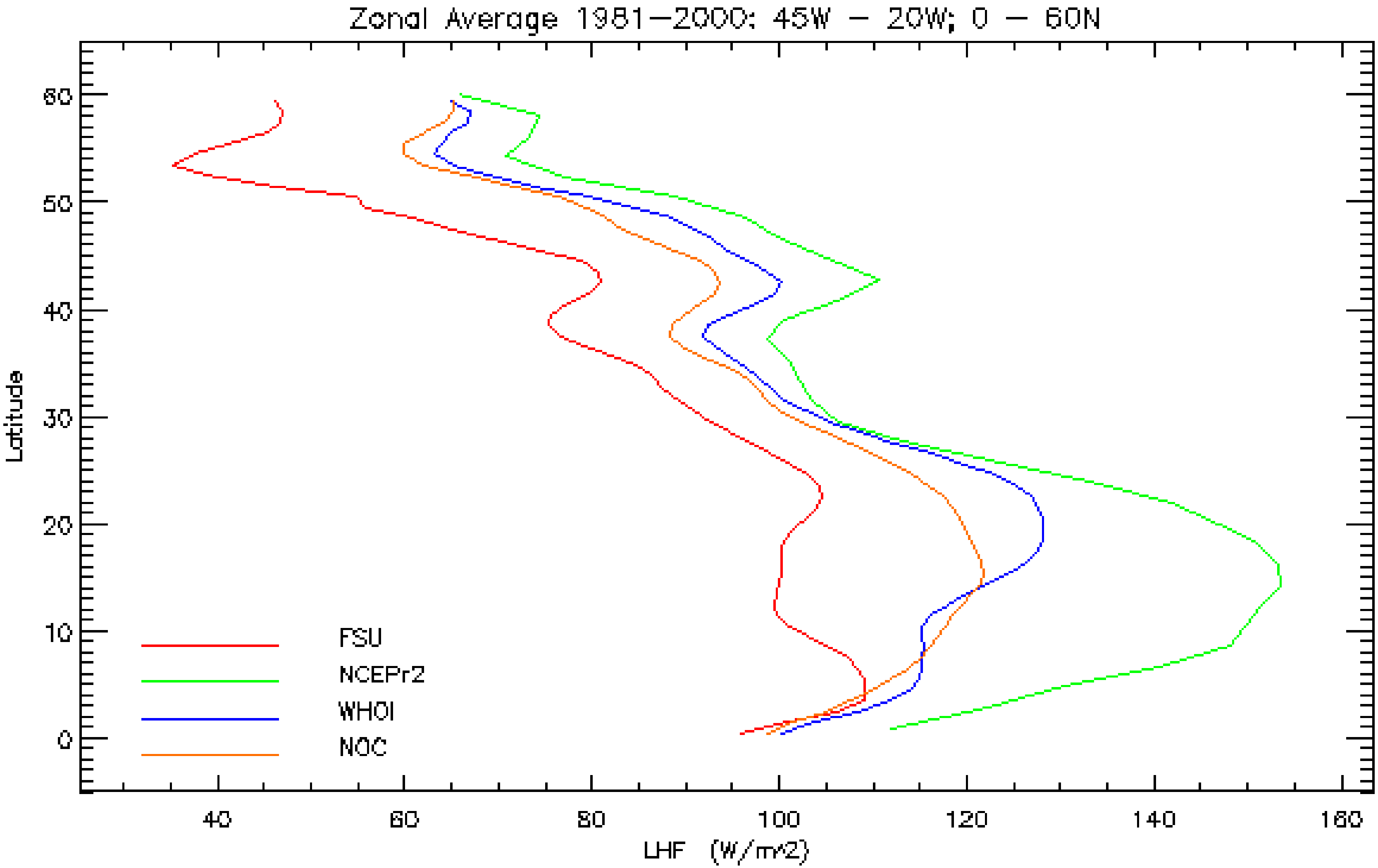
Forcing Product Inconstancies: Zonal Averaged Zonal Stress



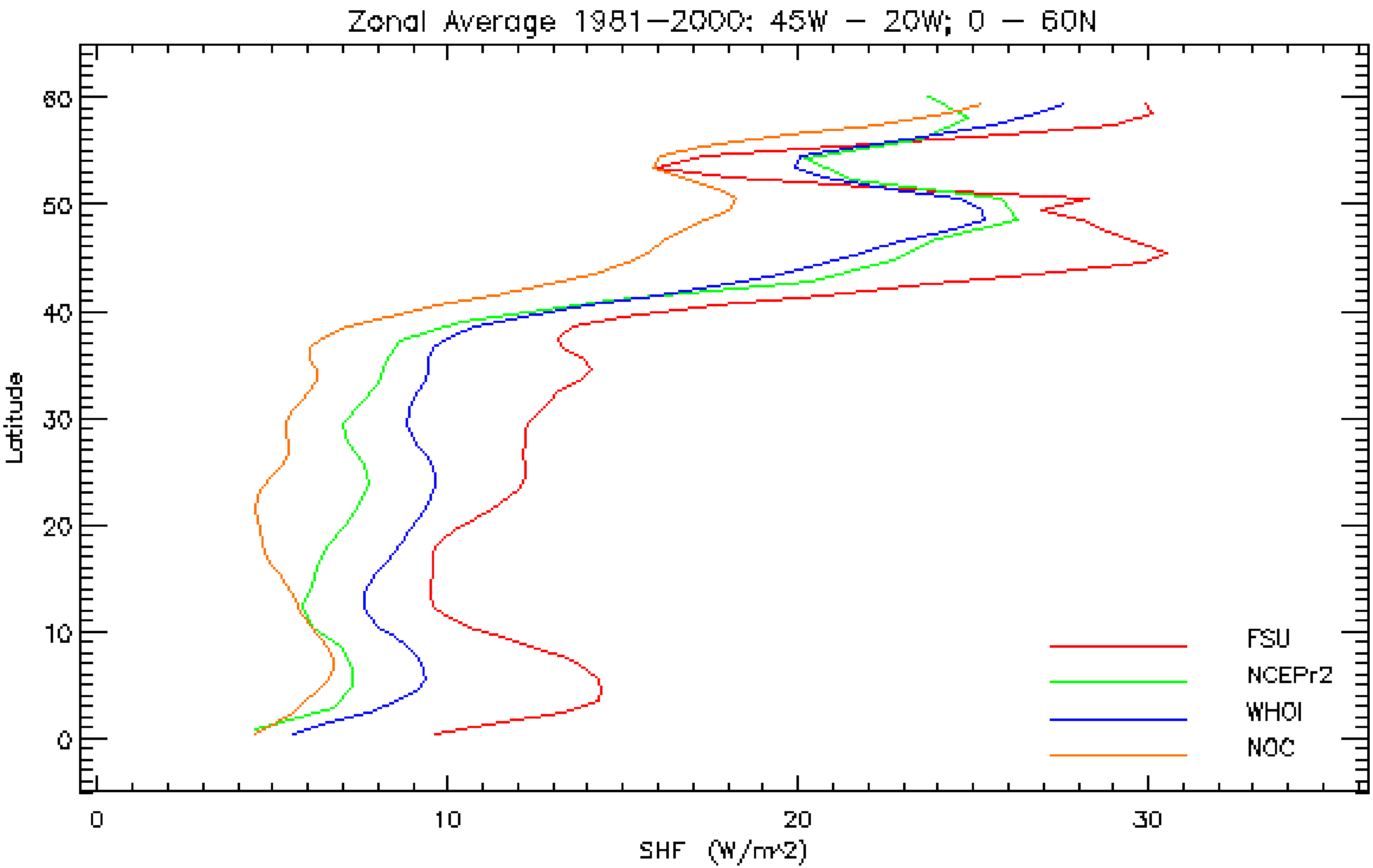
Forcing Product Inconstancies: Zonal Averaged Meridional Stress



Forcing Product Inconstancies: Zonal Averaged Latent Heat Flux



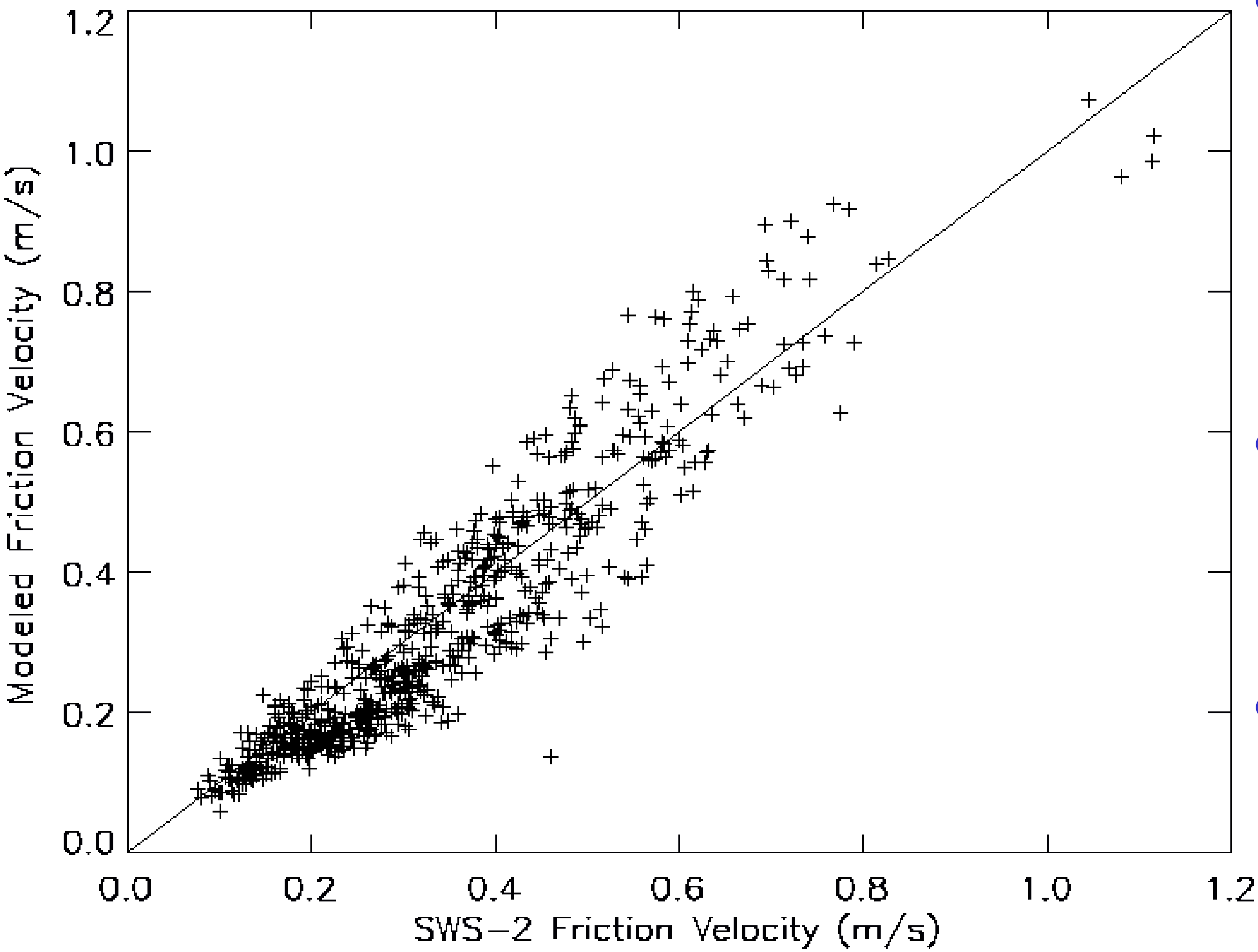
Forcing Product Inconstancies: Zonal Averaged Sensible Heat Flux



Input Data for Flux Algorithms

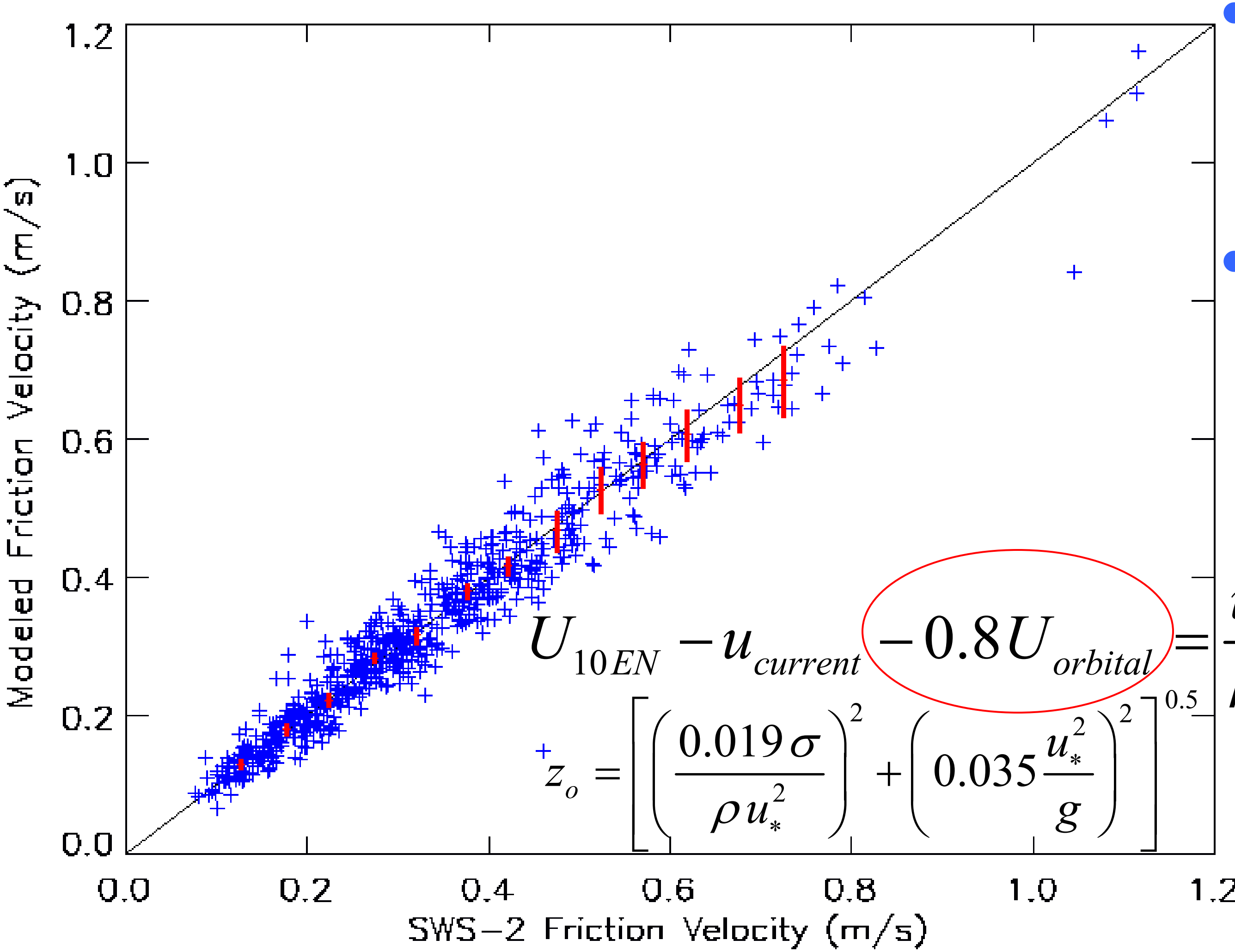
- Several studies have indicated that much better surface forcing can be achieved by using NWP values as input to good flux models.
- But what about the accuracy of the flux model?
  - Are there large difference between model parameterizations?
  - How good are the model inputs, and how sensitive are flux models to errors in these inputs?

Results of Taylor and Yelland's Parameterization on SWS2 data



- This parameterization is very good in comparison to most stress parameterizations.
- It has two tuning parameters, one more than usual.
- Largest wind speed in this data set is 24 ms^{-1}.

Results of Bourassa (2006) Compared to SWS2 Observations

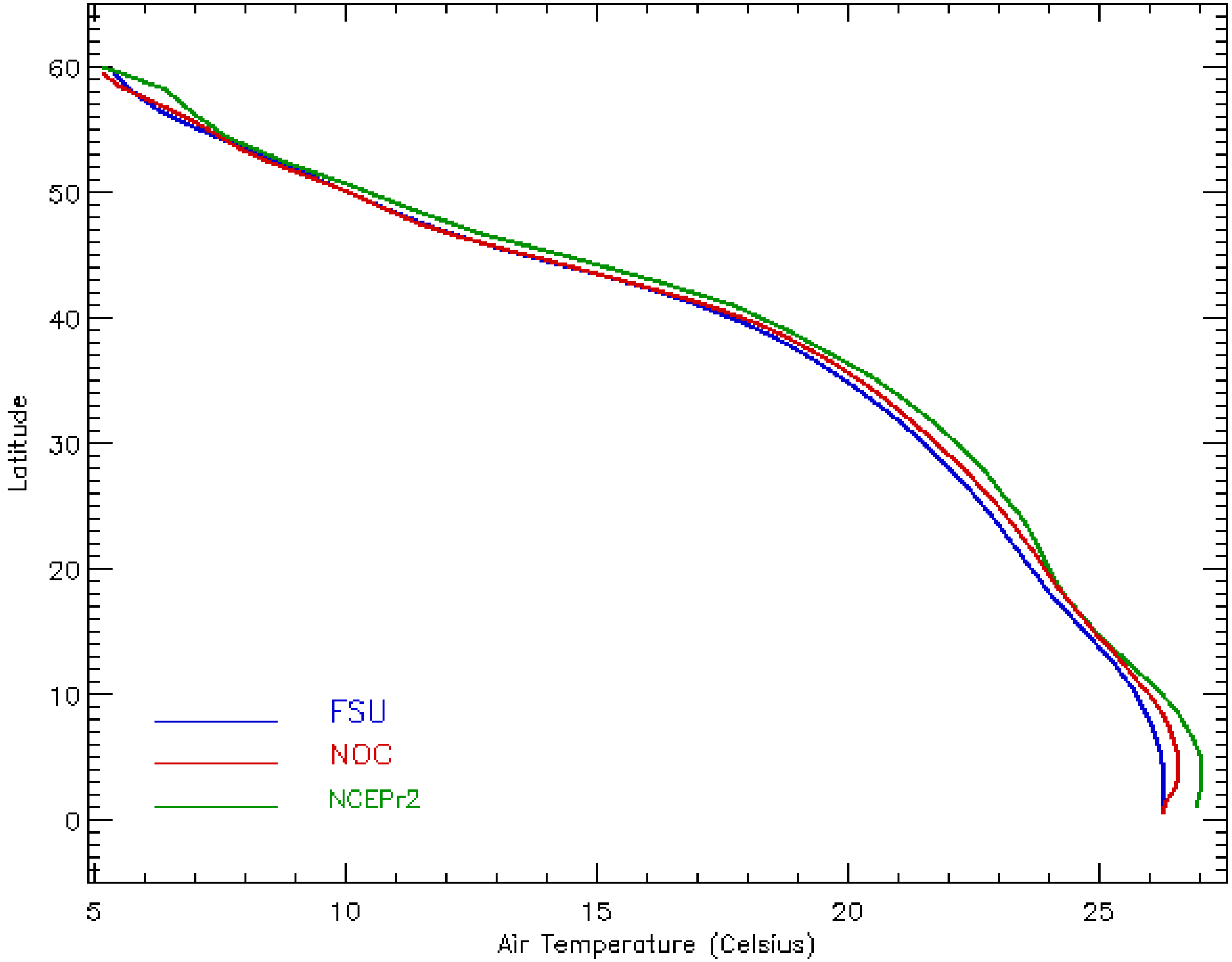


$$U_{10EN} - u_{current} - 0.8U_{orbital} = \frac{u_*}{k_v}\log\left(\frac{z - 0.8H_s}{z_o}\right)$$

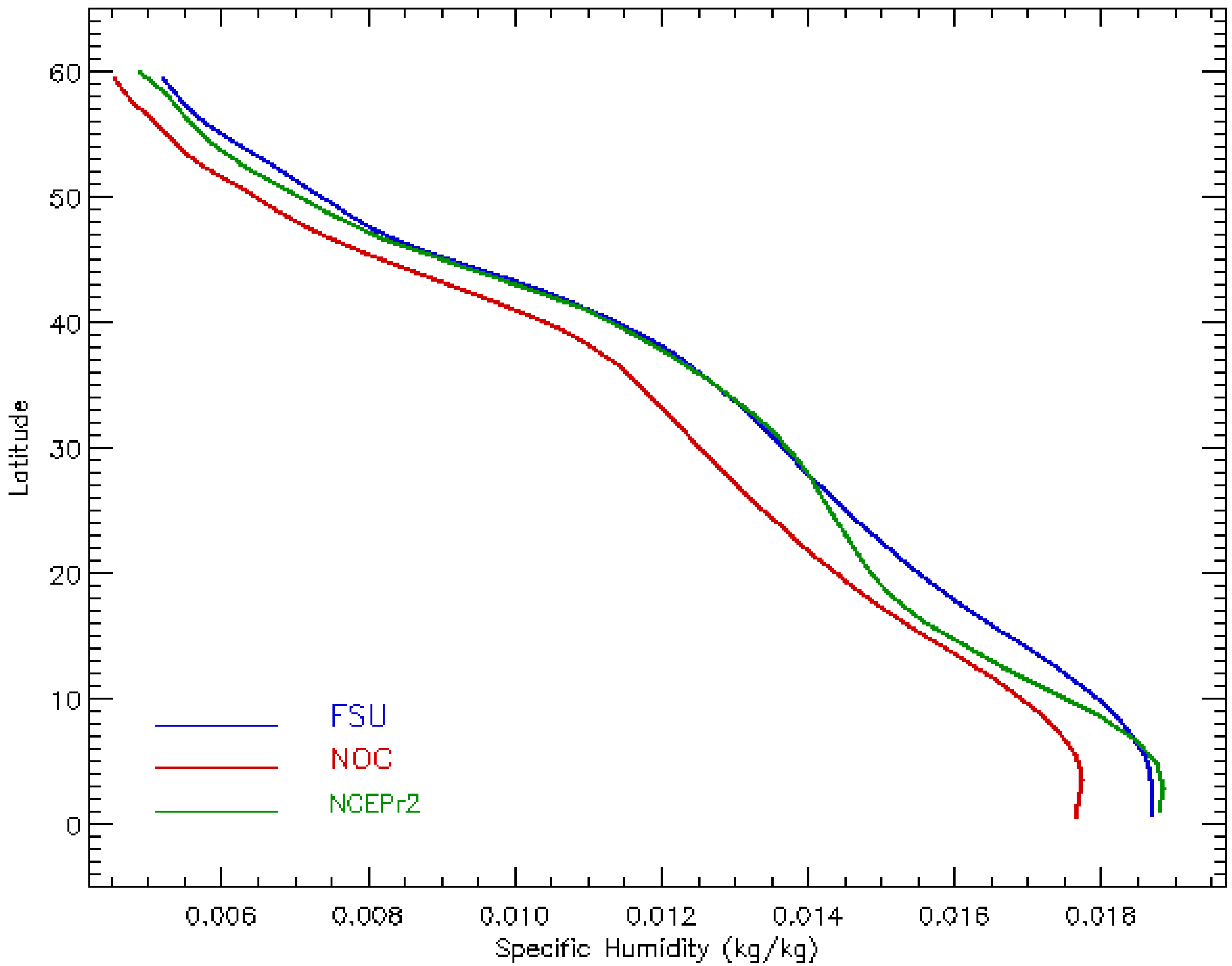
$$z_o = \left[\left(\frac{0.019\sigma}{\rho u_*^2}\right)^2 + \left(0.035\frac{u_*^2}{g}\right)^2\right]^{0.5}$$

- This variation has a non-zero displacement height.
- Displacement height is a fraction of the significant wave height.
- Charnock's constant is greatly reduced.

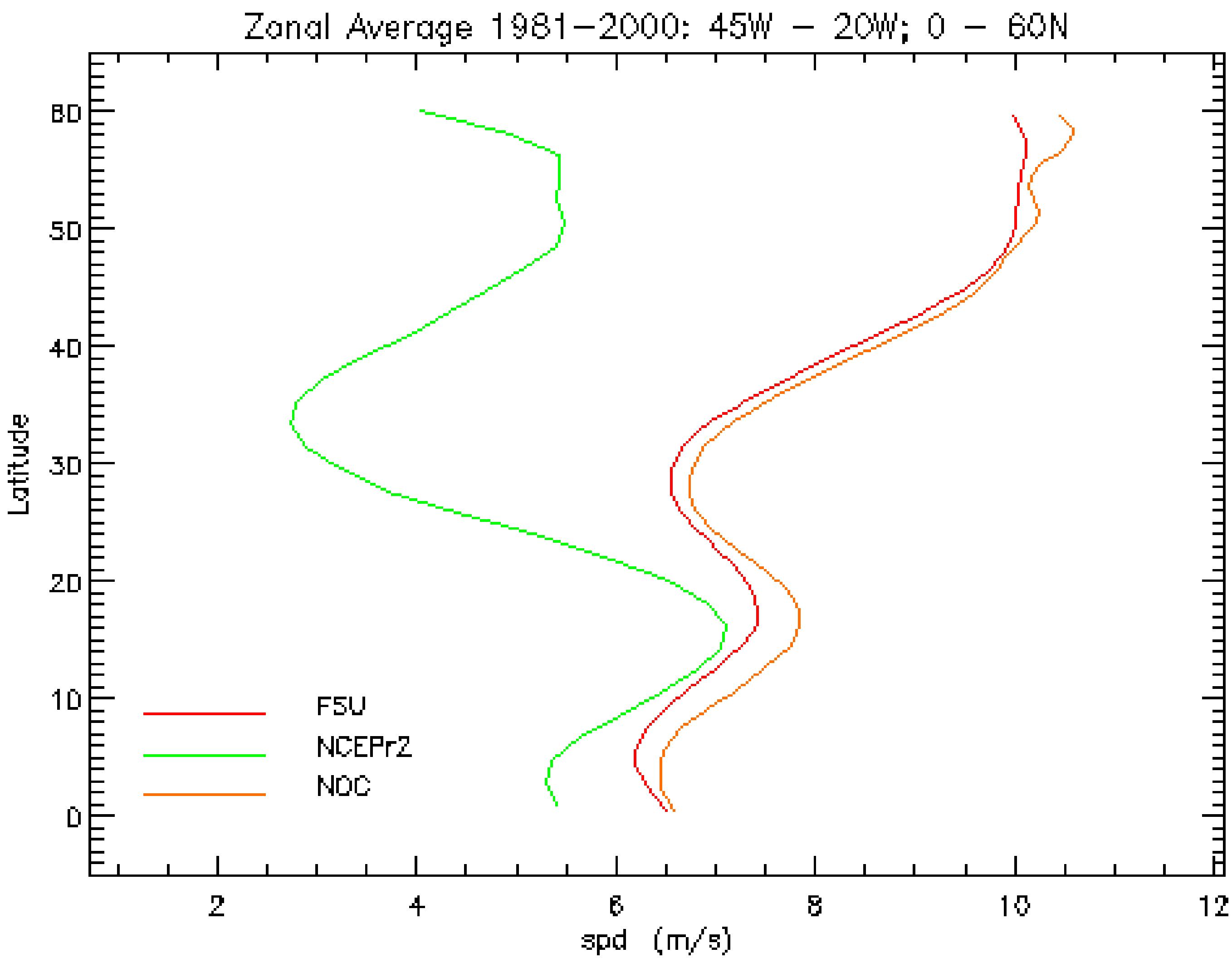
Zonal Averaged 10m Air Temperature



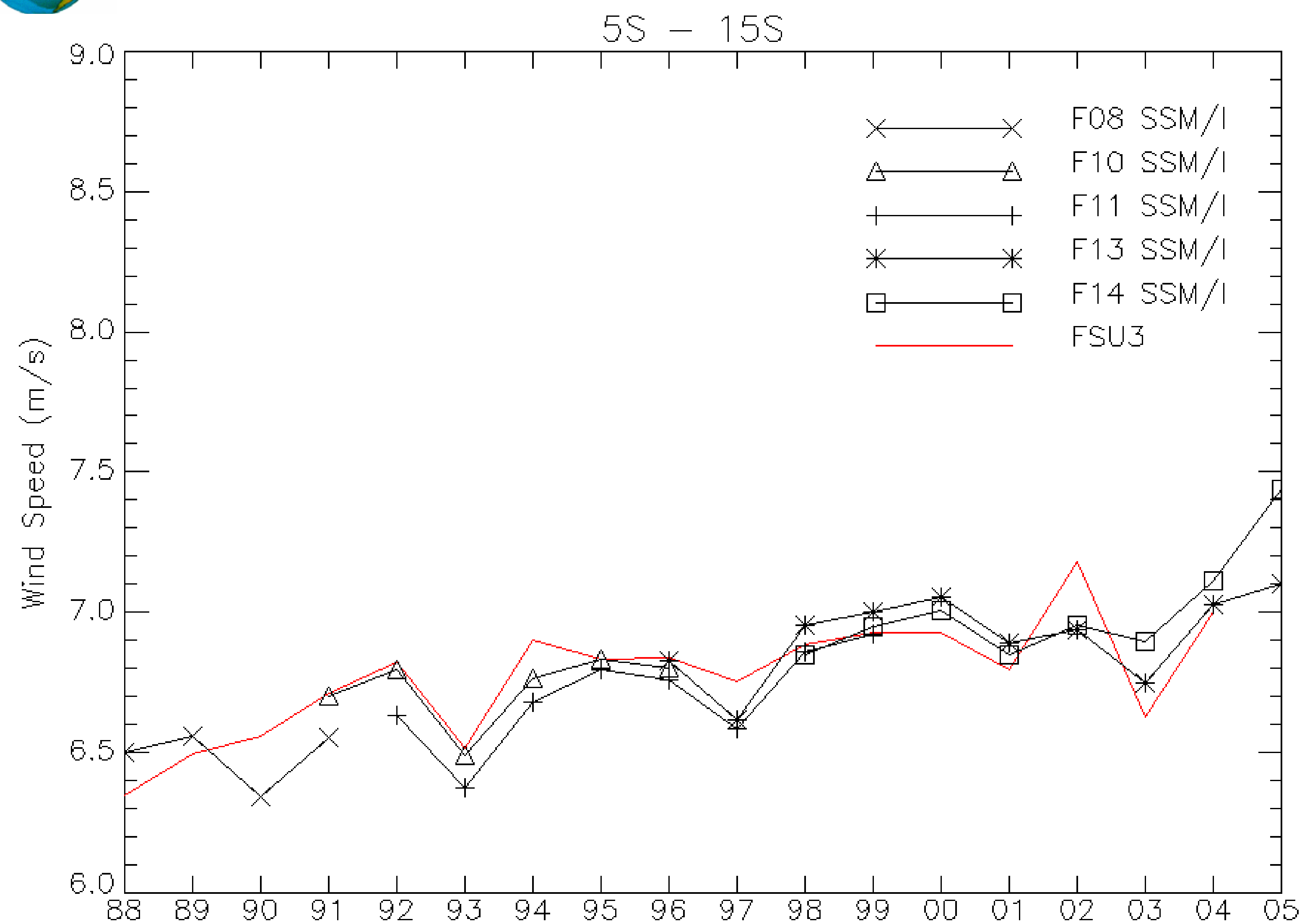
Zonal Averaged 10m Specific Humidity



Zonal Averaged Wind Speed



Comparison to Satellite



Historical and Modern Goals For Flux Accuracy

- During TOGA-COARE it was determined that a goal in surface turbulent flux observations was a bias of no more than $5Wm^{-2}$.
- This same goal is currently being stated in comments on decadal satellite survey.
- There have been several estimates on the observational accuracies required to achieve this goal.
- HOWEVER these accuracies were determined for the environments being observed during TOGA-COARE (the tropical Pacific Ocean).
  - The conditions in the tropical Pacific Ocean are somewhat different from other parts of the globe.
  - How much do the necessary observational accuracies change for different environments?

Suggested Measurement Accuracy From the Handbook

Table 1: Accuracy, precision and random error targets for SAMOS. Accuracy estimates are currently based on time scales for climate studies (i.e., ±10 W/m^2 for Q_{net} on monthly to seasonal timescales). Several targets are still to be determined.

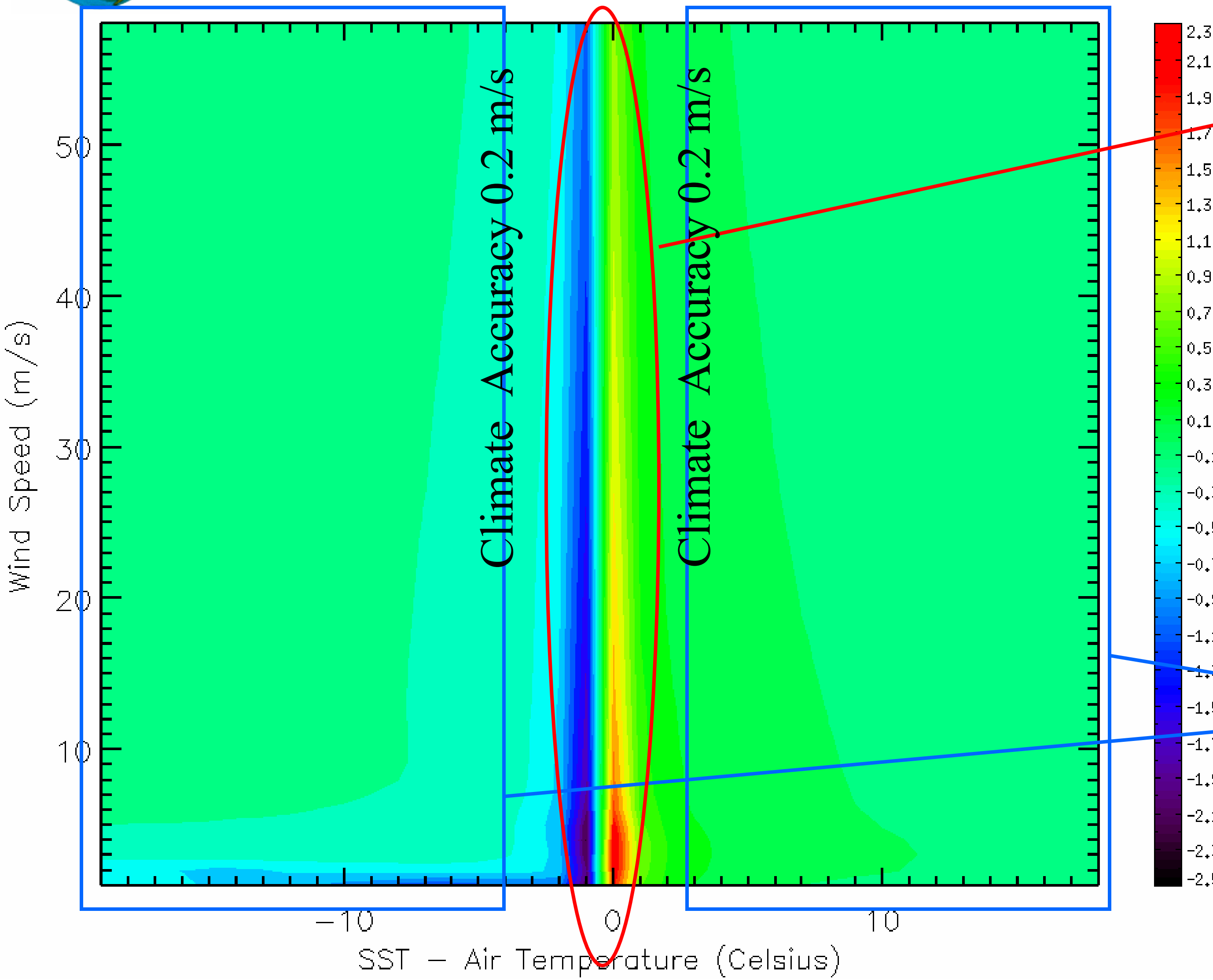
Parameter	Accuracy of Mean (bias)	Data Precision	Random Error (uncertainty)
Latitude and Longitude	0.001°	0.001°	
Heading	2°	0.1°	
Course over ground	2°	0.1°	
Speed over ground	Larger of 2% or 0.2 m/s	0.1 m/s	Greater of 10% or 0.5 m/s
Speed over water	Larger of 2% or 0.2 m/s	0.1 m/s	Greater of 10% or 0.5 m/s
Wind direction	3°	1°	
Wind speed	Larger of 2% or 0.2 m/s	0.1 m/s	Greater of 10% or 0.5 m/s
Atmospheric Pressure	0.1 hPa (mb)	0.01 hPa (mb)	
Air Temperature	0.2 °C	0.05 °C	
Dewpoint Temperature	0.2 °C	0.1 °C	
Wet-bulb Temperature	0.2 °C	0.1 °C	
Relative Humidity	2%	0.5 %	
Specific Humidity	0.3 g/kg	0.1 g/kg	
Precipitation	~0.4 mm/day	0.25 mm	
Radiation (SW in, LW in)	5 W/m^2	1 W/m^2	
Sea Temperature	0.1 °C	0.05 °C	
Salinity			
Surface Current	0.1 m/s	0.05 m/s	

- I will assume that a 5Wm^{-2} is the limit for biases in radiative fluxes.
- Then 5Wm^{-2} is the limit for biases in surface turbulent heat fluxes.

Observational Errors

- Errors can be described as composed of
  - A bias (this bias could be a function of environmental conditions),
  - And a random uncertainty.
  - The same information can be used to determine the influence of the bias and the uncertainty.
- We are primarily interested in how biases in observations of wind speed (w), sea surface temperature (SST), near surface air temperature (T_{air}), and near surface humidity (q_{air}) translate to biases in calculated fluxes.
  - Sensible heat (H), latent heat (E), and stress (τ).
- In general, the bias in one of these observations can be related to the bias in a flux through a Sensitivity (S).

Example: How Much Bias in Wind Speed Can We Tolerate in Calculated SHF

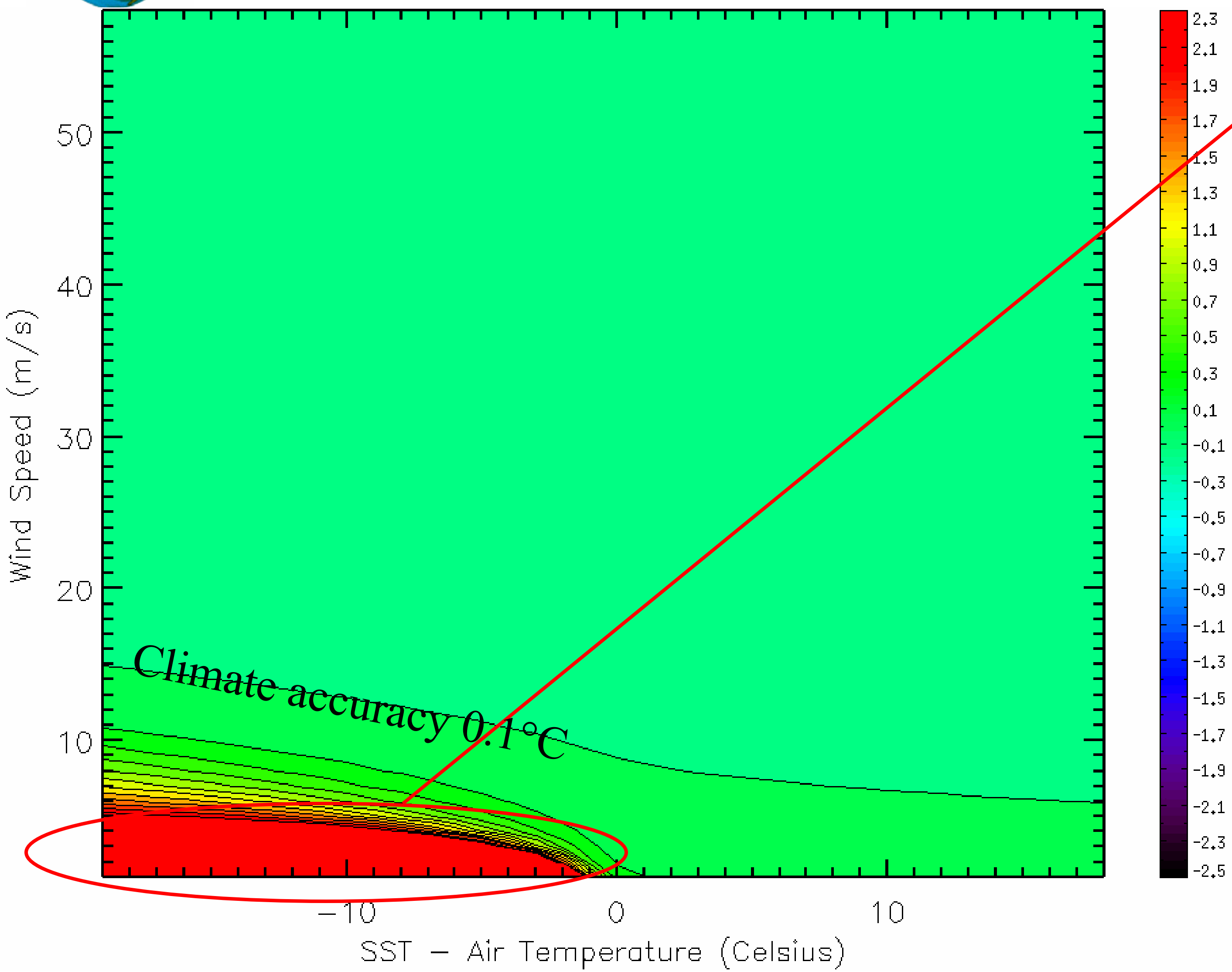


- We can be relatively sloppy.

Assume a bias in SHF of <1.25 Wm^{-2} is OK.

- We must be relatively accurate.

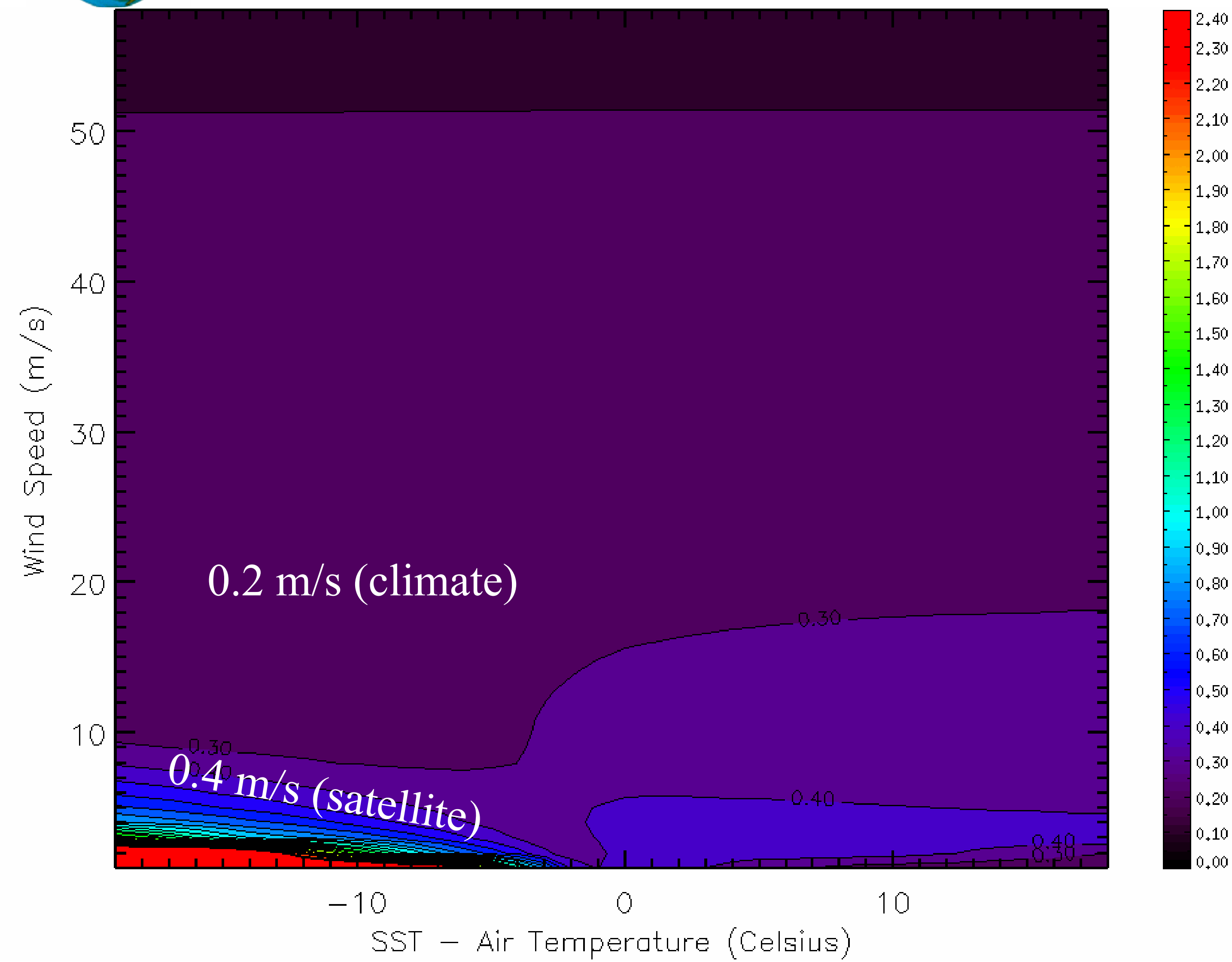
Example: How Much Bias in SST Can We Tolerate in Calculated SHF



- We can be extremely sloppy.

Assume a bias in SHF of <1.25 Wm^{-2} is OK.

Example: How Much Bias in Wind Speed Can We Tolerate in Calculated LHF



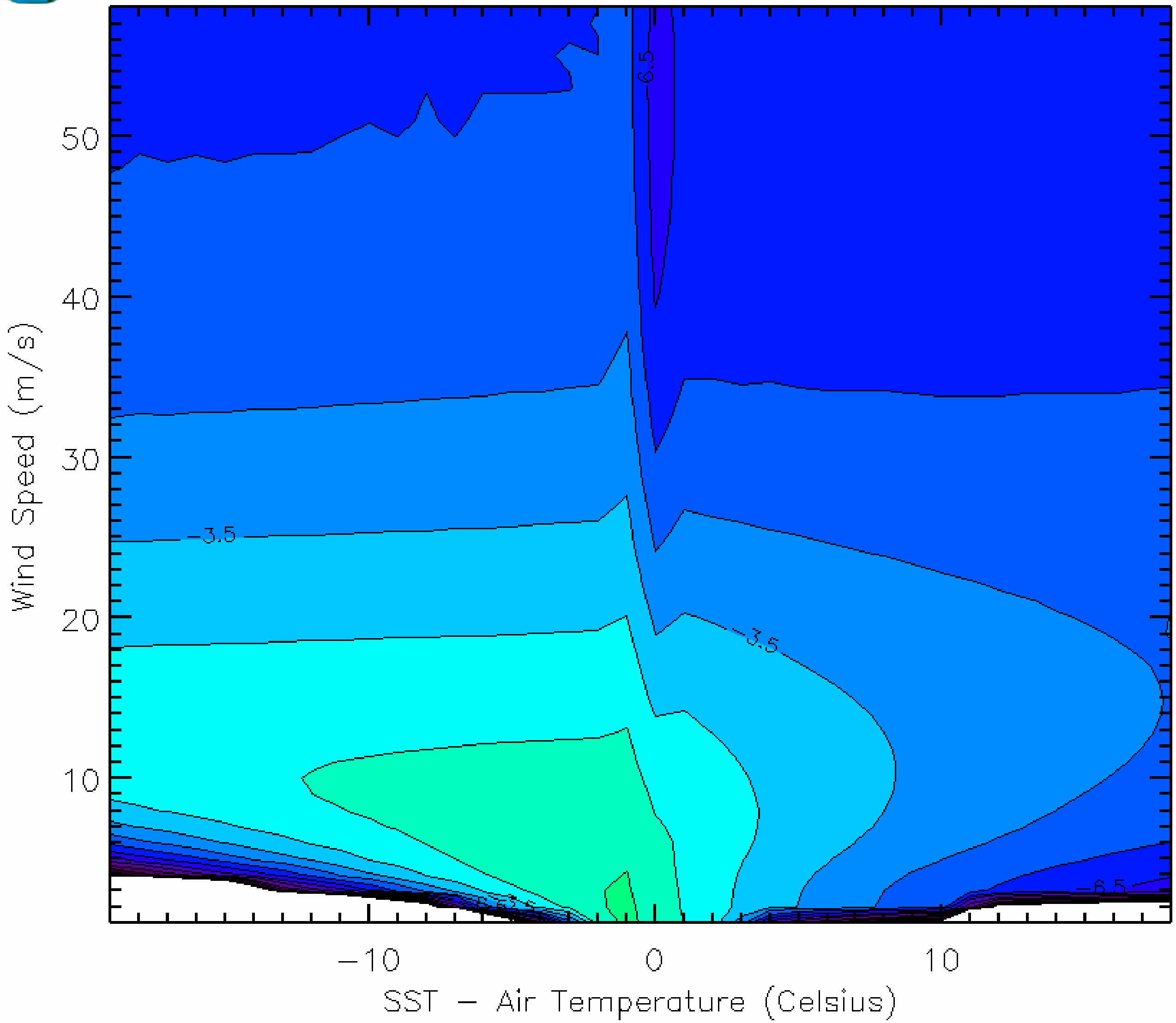
Fortunately, high winds are usually associated with unstable stratification ($SST - T_{air} > 0$).

In strong storms, we will not meet our accuracy requirement.

Conclusions

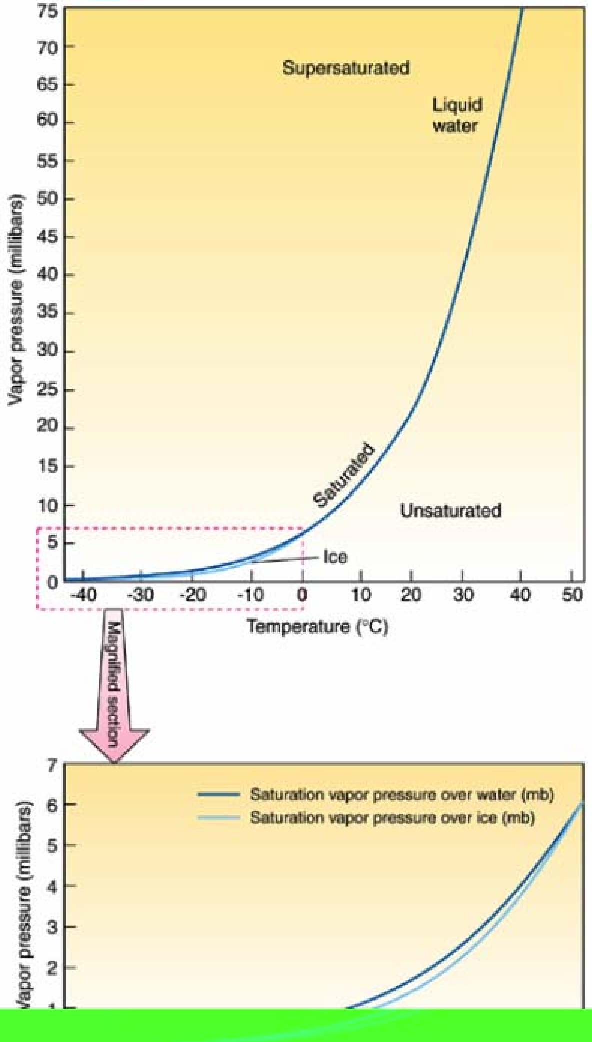
- Surface forcing differs too much from product to product.
- There are large differences in fluxes due to
  - Differences in flux parameterization,
  - Differences in input to flux parameterizations.
- The biases in some NWP input for flux models are far greater than the maximum desired biases to be under a $5Wm^{-2}$ biases in heat fluxes.
  - For conditions with high wind speeds or large air/sea temperature differences, we are likely to have very large errors in fluxes because a small bias translates to a large error.
- A great deal of the seemly random error in surface stress can be removed by properly considering waves (and currents).
- It remains to be seen how much of the improvement in stress translates to improvements in heat fluxes.

How Much Bias in Air Temperature Can We Tolerate in Calculated LHF



- Not a problem!

Saturation Vapor Pressure

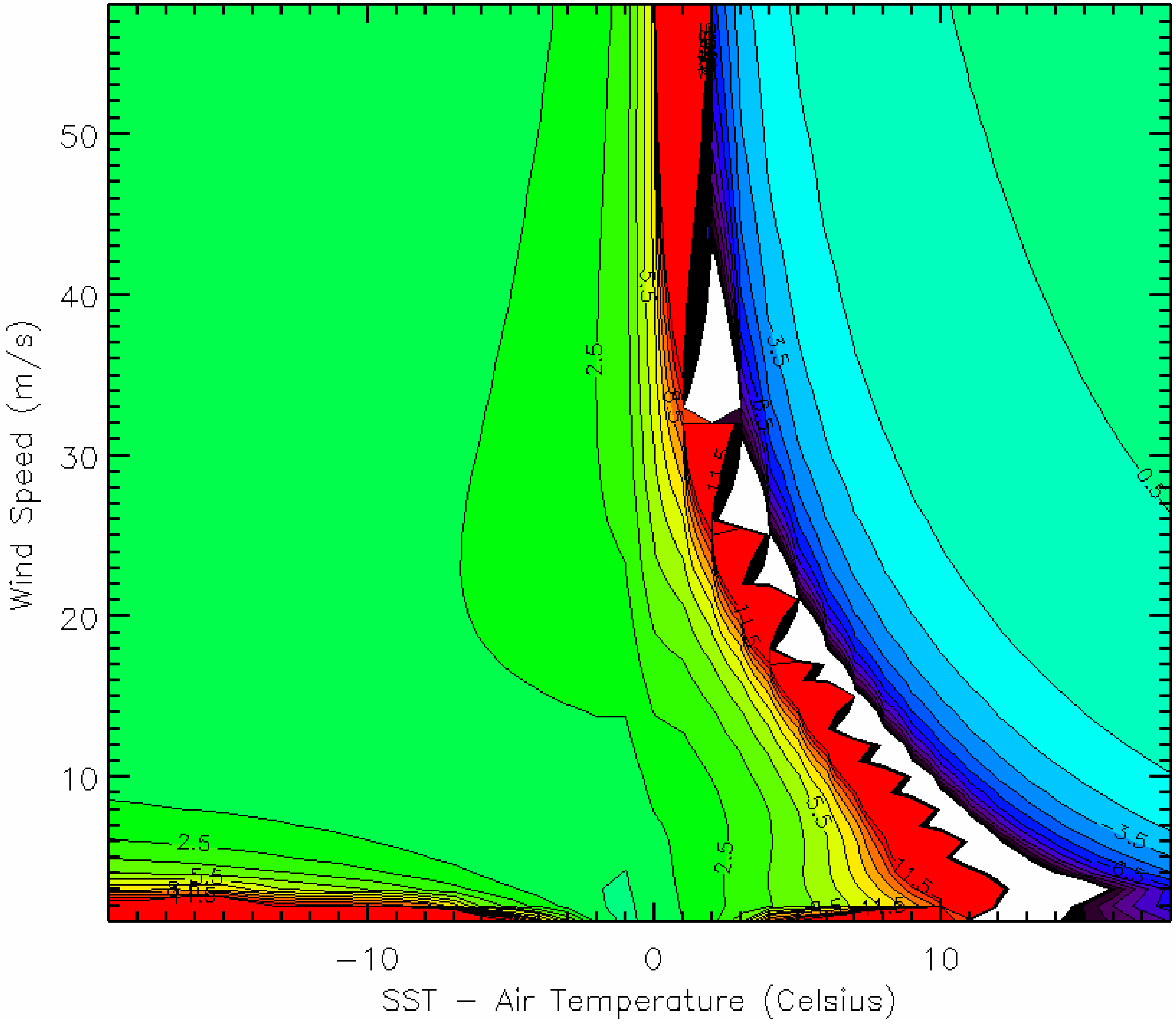


- 'Surface' humidity is considered to be 98% or 100% of the saturation value, which is a strong function of temperature.
- The Clausius-Clapeyron equation describes how the saturation vapor pressure changes with temperature.

$$e_s = e_o \exp\left[\frac{L}{R_v}\left(\frac{1}{T_o} - \frac{1}{T}\right)\right]$$

  - where e_o = 0.611 kPa, T_o = 273K, and R_v = 461 $JK^{-1}kg^{-1}$ is the gas constant for water vapor.
  - L is either the latent heat of vaporization (L_v = 2.5x10^6 Jkg^{-1}), or the latent heat of deposition (L_d = 2.83x10^6 Jkg^{-1}), depending on whether or not we are describing equilibrium wit[illegible]

How Much Bias in SST Can We Tolerate in Calculated LHF?

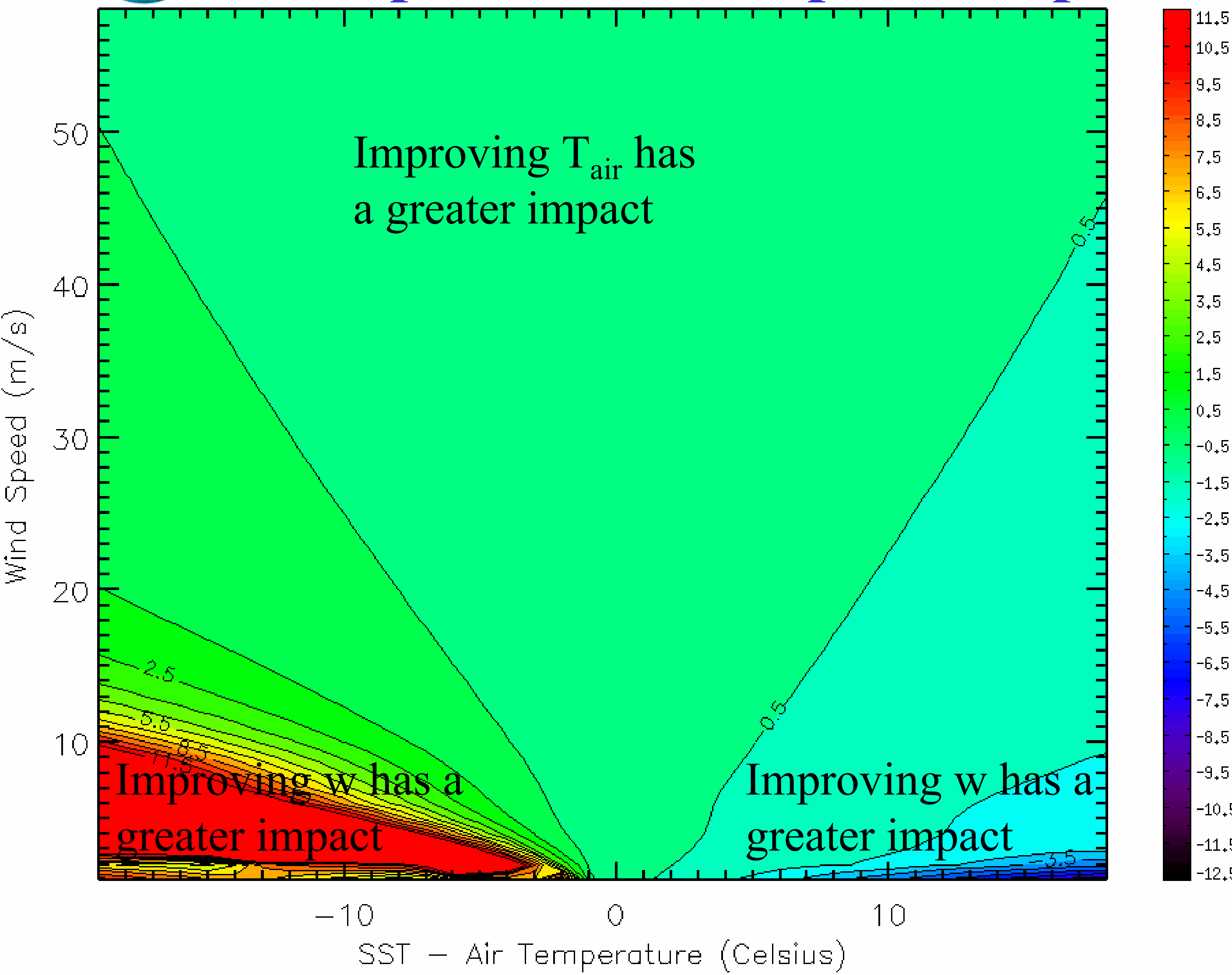


- Recall that these numbers should be divided by Δq (in g/kg).
- For low temperature regions, we might what tighter accuracies than have been specified.
- In areas with large Δq, there could be issues for very high winds and unstable stratification.
  - Particularly so for point comparisons

Maximize Benefits of Improvements in Observations

- How do we decide which instruments to improve?
- A ratio of sensitivities provides some indication of where improvements to accuracy will have the greatest influence. That is, which type of observation is the best to improve.
  - Technically this should be weighted by the cost and time involved in the improvement.
  - However, if you can estimate that it will take $x to make a certain amount of improvement, you can determine where the money is best spent.

When Will Improved Accuracy in Air Temperature and Speed Help The Most?



- Examine the relative sensitivity of SHF to errors in T_{air} and wind speed: $\partial H/\partial w \,/\, \partial H \partial T_{air}$
- A ratio of 1 indicates an improvement of *x* m/s will equal the improvement of *x* °C

Random Errors

- If the random errors have a Gaussian distribution, which might be expected from the *central limit theorem*, then random errors are described by a standard deviation (σ, which is used a measure of spread).
- If the latent heat flux (E) is written as a function of the input variables:
  - $E = f(x_1, x_2, x_3, x_4)$,
  - Then the uncertainty in E (σ_E) for a single observation can be written as

$$\sigma_E^2 = \sum_i \left(\frac{\partial f}{\partial x_i} \sigma_{x_i} \right)^2$$

$$\sigma_E^2 = \left(\frac{\partial E}{\partial w} \right)^2 \sigma_w^2 + \left(\frac{\partial E}{\partial T_{air}} \right)^2 \sigma_{T_{air}}^2 + \left(\frac{\partial E}{\partial SST} \right)^2 \sigma_{SST}^2 + \left(\frac{\partial E}{\partial q_{air}} \right)^2 \sigma_{q_{air}}^2$$

- An uncertainty in the mean is equal to σ_E divided by the squareroot of the number of independent observations.

Take Home Messages

- The type(s) of error (bias, random, sampling) that are relevant depend on the application.
- Errors (or uncertainties) in observed variables can be used to determine the biases (and uncertainties) in calculated variables.
- The same sensitivity tables can used to determine both random errors and biases.
- The current suggestions for accuracies are for the most part good enough for many applications; however, there are conditions for which they are insufficient.
- Ratios of these sensitivities provides some insight into which instruments to improve to improve fluxes.
- Suggested changes to accuracies:
  - Tighter requirements for mean wind speed?
  - Tighter mean SST accuracy would be nice, but can we do it?
  - Tighter requirements preferred for satellite calibration.

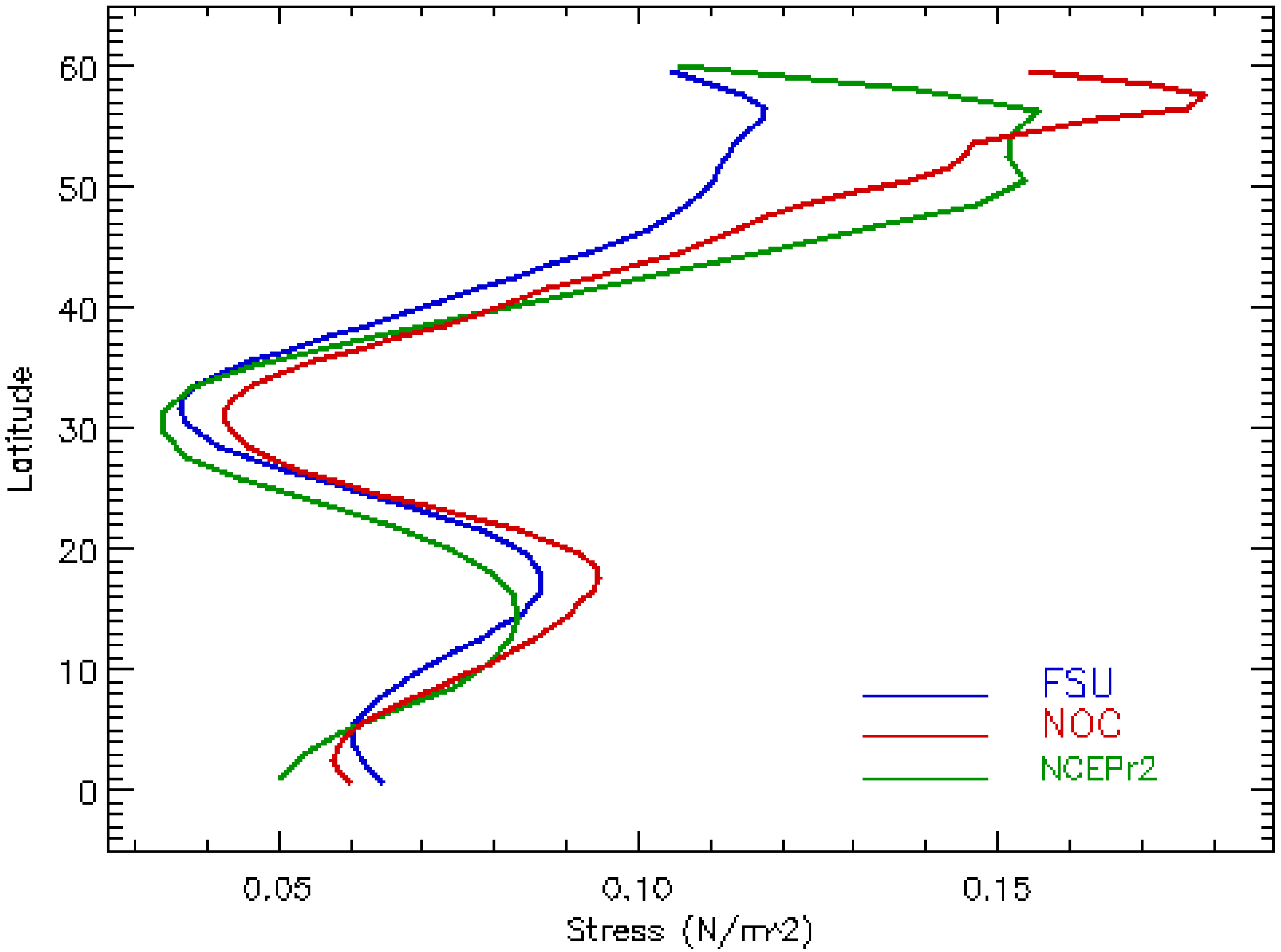
Suggested Measurement Accuracy From the Handbook

Table 1: Accuracy, precision and random error targets for SAMOS. Accuracy estimates are currently based on time scales for climate studies (i.e., ±10 W/m^2 for Q_{net} on monthly to seasonal timescales). Several targets are still to be determined.

Parameter	Accuracy of Mean (bias)	Data Precision	Random Error (uncertainty)
Latitude and Longitude	0.001°	0.001°	
Heading	2°	0.1°	
Course over ground	2°	0.1°	
Speed over ground	Larger of 2% or 0.2 m/s	0.1 m/s	Greater of 10% or 0.5 m/s
Speed over water	Larger of 2% or 0.2 m/s	0.1 m/s	Greater of 10% or 0.5 m/s
Wind direction	3°	1°	
Wind speed	Larger of 2% or 0.2 m/s	0.1 m/s	Greater of 10% or 0.5 m/s
Atmospheric Pressure	0.1 hPa (mb)	0.01 hPa (mb)	
Air Temperature	0.2 °C	0.05 °C	
Dewpoint Temperature	0.2 °C	0.1 °C	
Wet-bulb Temperature	0.2 °C	0.1 °C	
Relative Humidity	2%	0.5 %	
Specific Humidity	0.3 g/kg	0.1 g/kg	
Precipitation	~0.4 mm/day	0.25 mm	
Radiation (SW in, LW in)	5 W/m^2	1 W/m^2	
Sea Temperature	0.1 °C	0.05 °C	
Salinity			
Surface Current	0.1 m/s	0.05 m/s	

Wave data

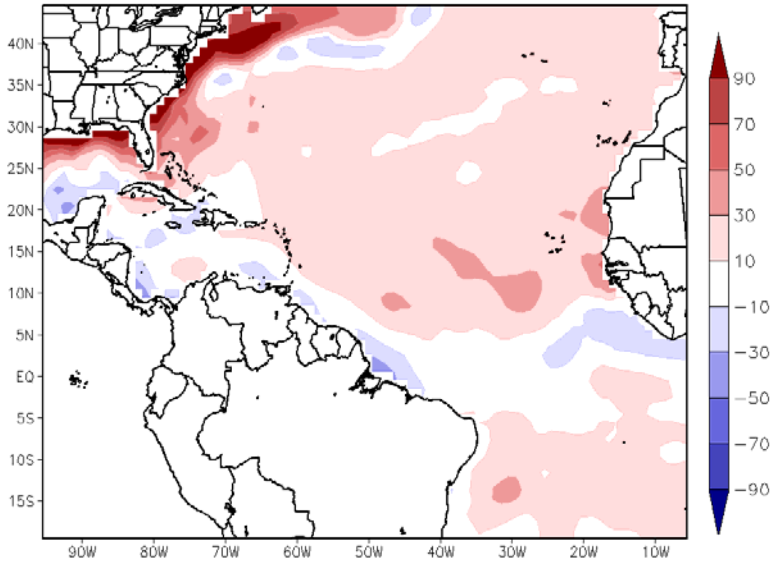
Forcing Product Inconstancies: Zonal Averaged Stress Magnitude



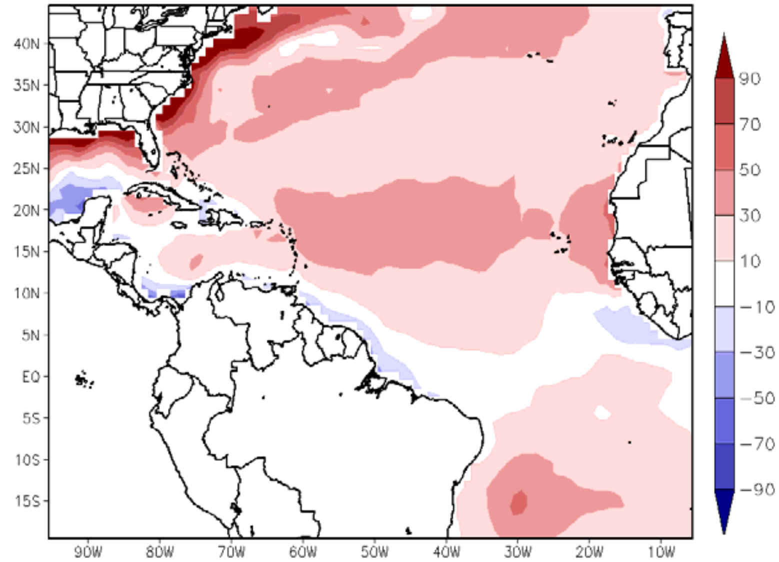
Flux Product Comparison

Latent Heat Flux: DJF (1982-2002)

NOC minus FSU3



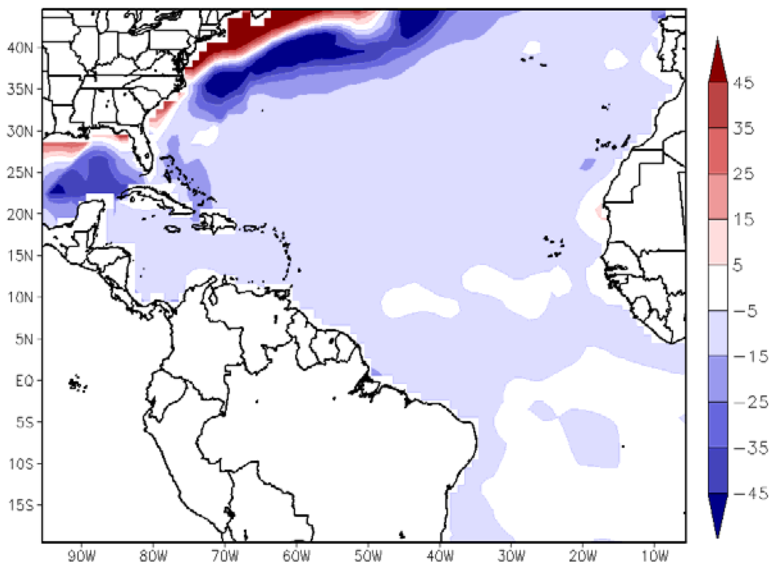
WHOI minus FSU3



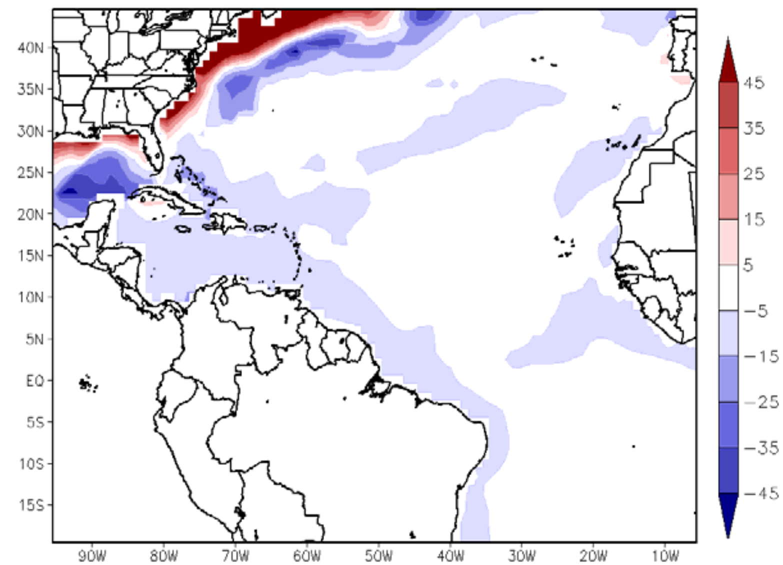
Flux Product Comparison

Sensible Heat Flux: DJF (1982-2002)

NOC minus FSU3



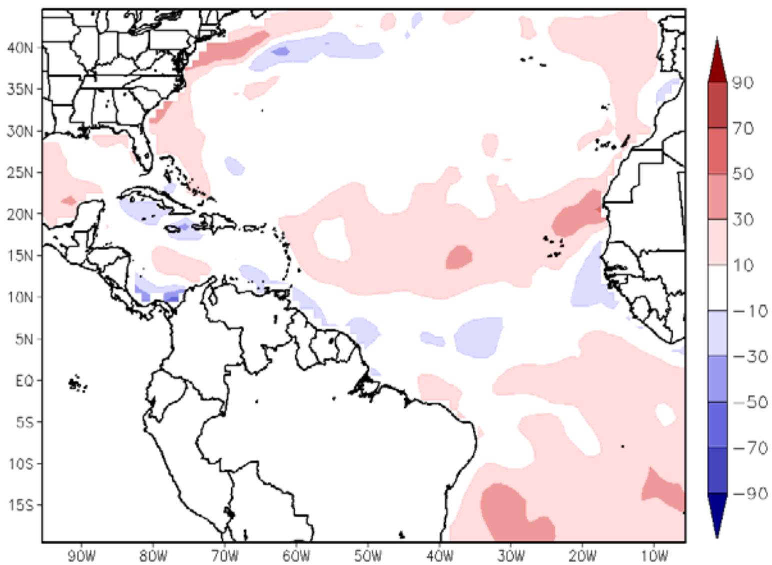
WHOI minus FSU3



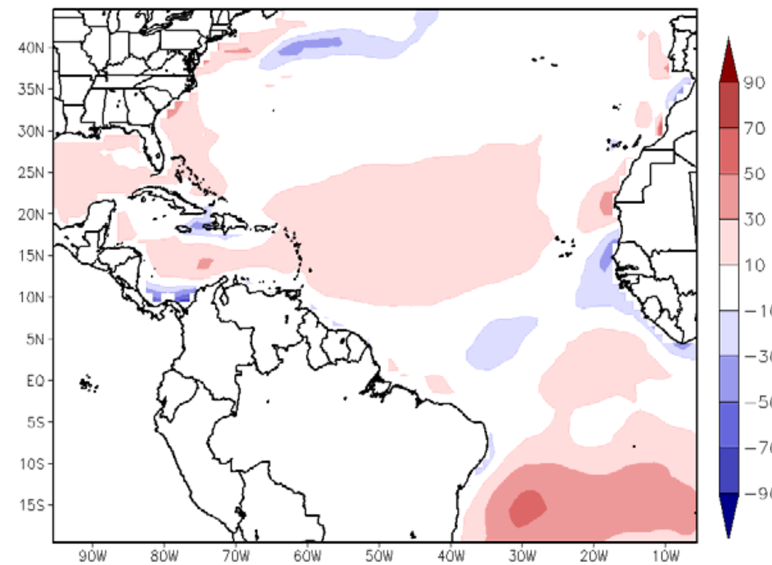
Flux Product Comparison

Latent Heat Flux: JJA (1982-2002)

NOC minus FSU3



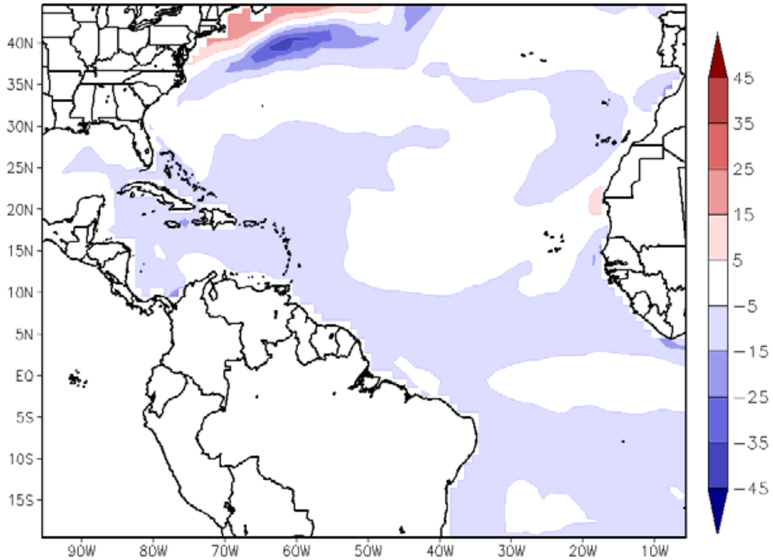
WHOI minus FSU3



Flux Product Comparison

Sensible Heat Flux: JJA (1982-2002)

NOC minus FSU3



WHOI minus FSU3