Surface Turbulent Fluxes and Scatterometry

Mark A. Bourassa

With input from Paul Hughes and Ryan Maue

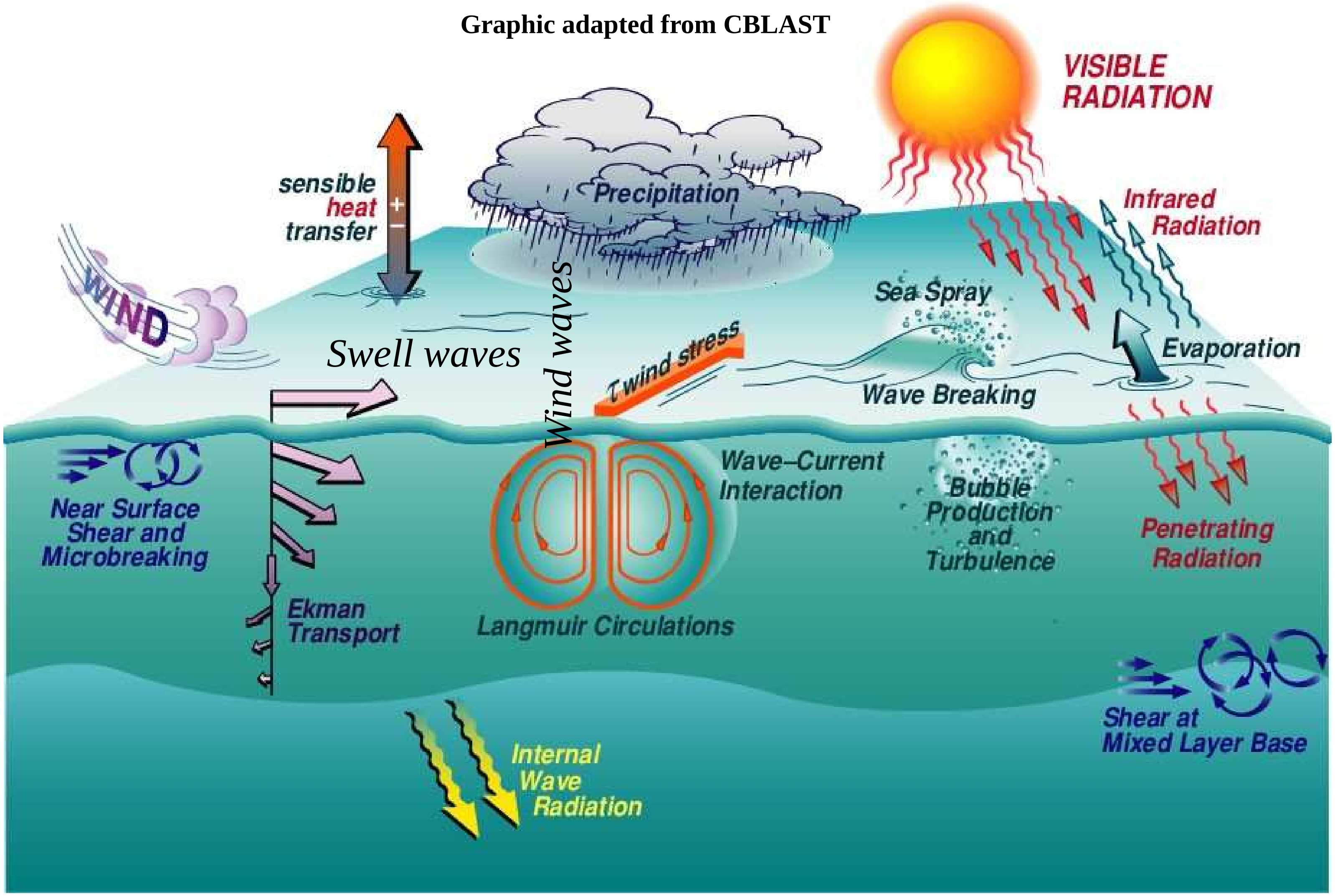
Center for Ocean-Atmospheric Prediction Studies &
Department of Meteorology

The Florida State University, USA

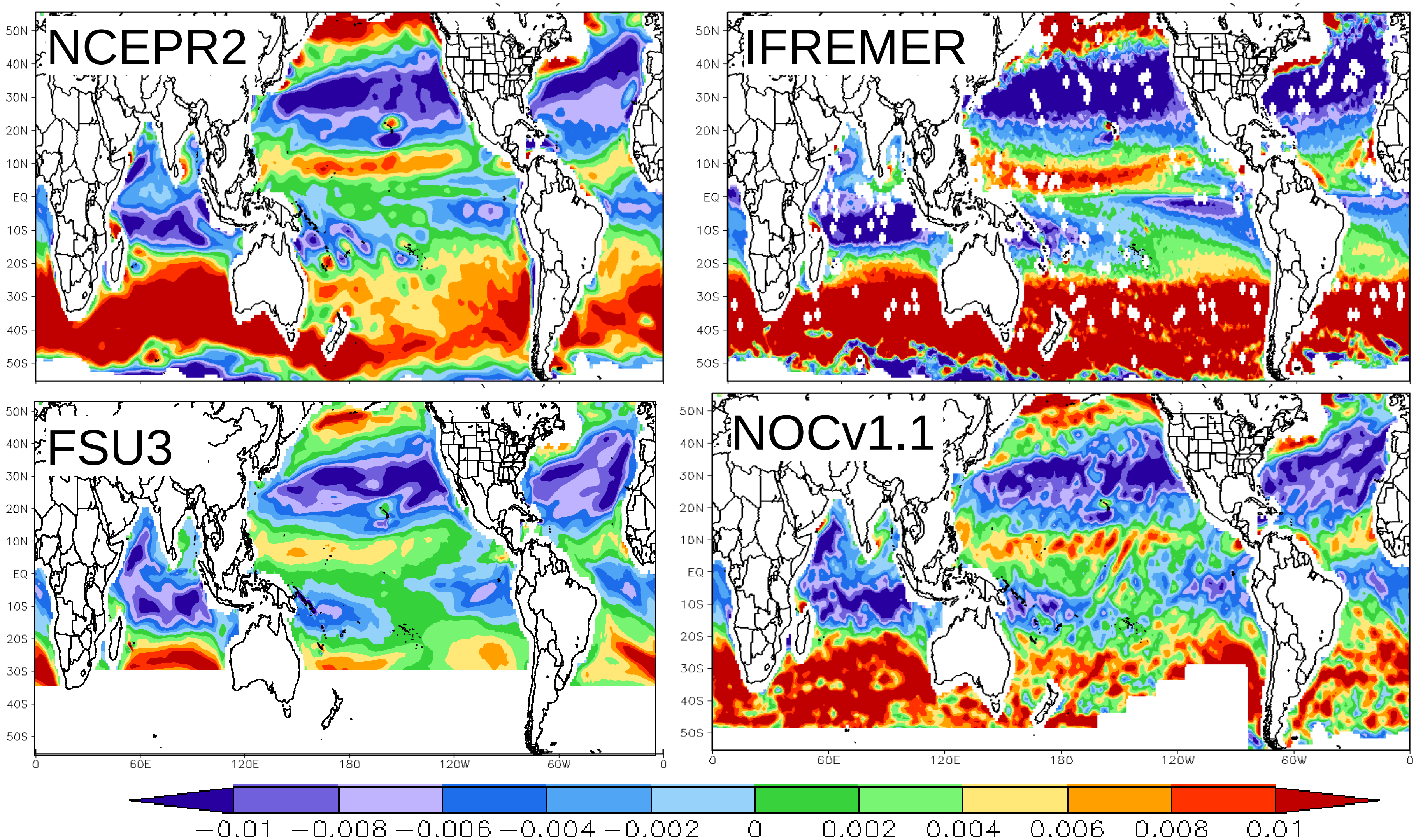
Many Air/Sea Interaction Processes

- Most are strongly influenced by stress -

Graphic adapted from CBLAST

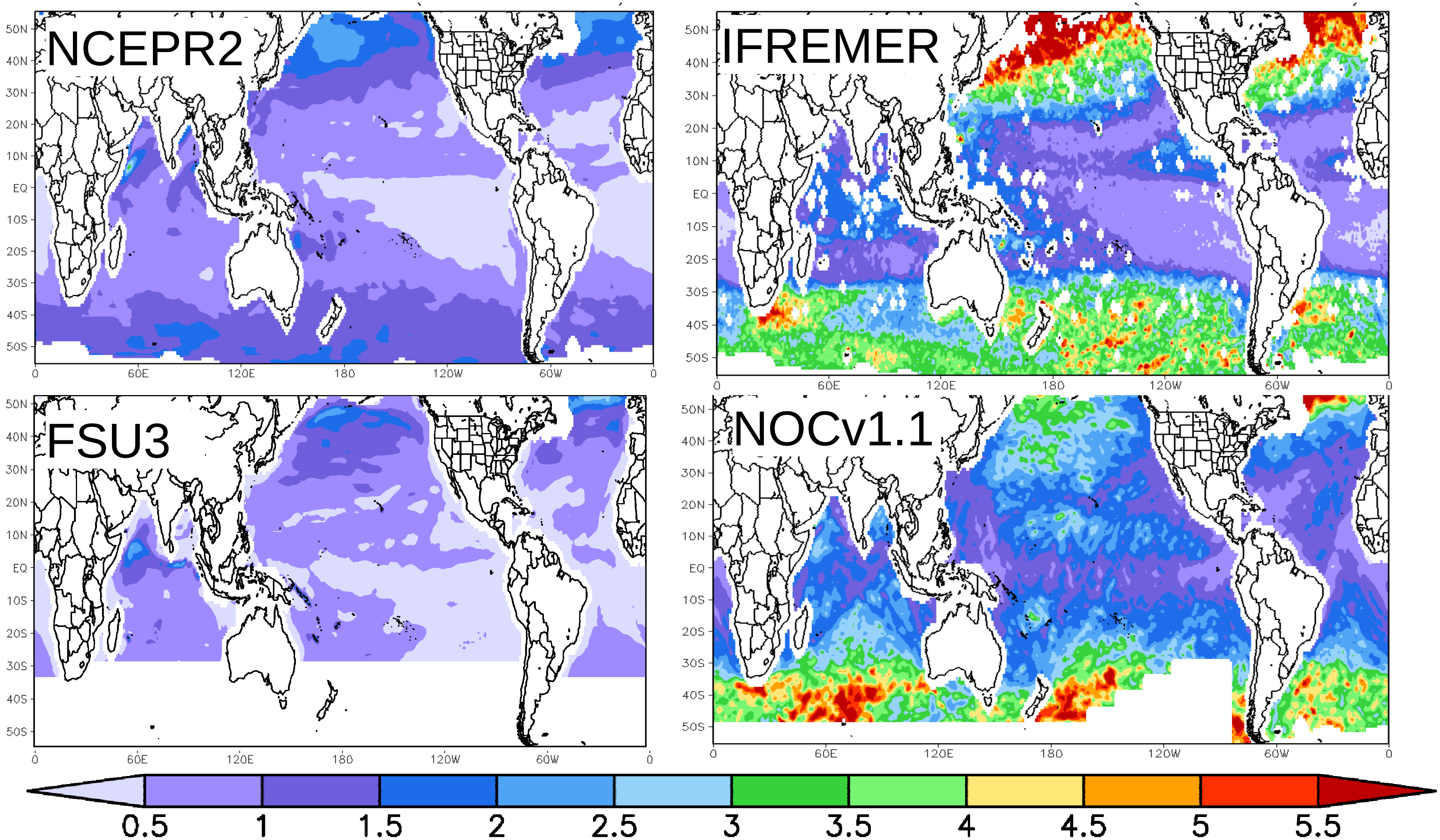


Curl of the Stress



- Ship tracks are apparent in many products, as are TAO buoys

Standard Deviation of the Curl of the Stress

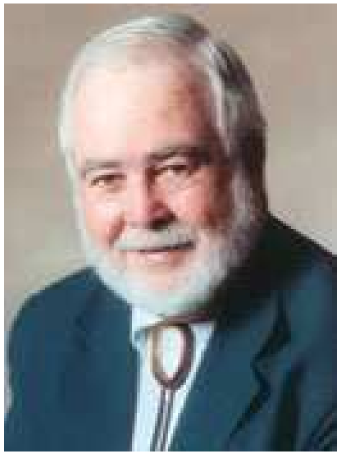


- Ship tracks are apparent in many products, as are TAO buoys

Issues to be Addressed

- Does a scatterometer respond to stress rather than other alternatives (e.g., wind or equivalent neutral wind)?
- How much does sub-monthly variability in winds and other variables influence the latent heat flux?
  - Quite a few people suggest that there is little impact
  - A few say it is a big deal
  - Magnitude has never been determined
- Biases due to treating satellite winds as ship winds
  - Focusing on wave issues

Why Calibrate to 'Winds' Rather than Stress



- Radar backscatter was observed to be dependent on wind speed and/or wave height in the 1950s.
- In 1963 Dick Moore had the idea that backscatter could be used to estimate oceanic variables.
- The NASA Sea Surface Stress (S^3) report indicated that scatterometers probably did respond to stress rather than wind.
- The number of stress observations available for calibration was approximately zero. Therefore it was desirable to calibrate to wind, for which the collocated observations would be plentiful.
- Willard Pierson, Vince Cardone and colleagues found that wind speed could be adjusted to be more consistent with surface stress.
  - Equivalent neutral wind

Wind or Stress?

- The surface turbulent stress (momentum flux density) is usually parameterized as

$$\tau = \rho C_D U_{10}^2$$

- This form can be more accurately written as

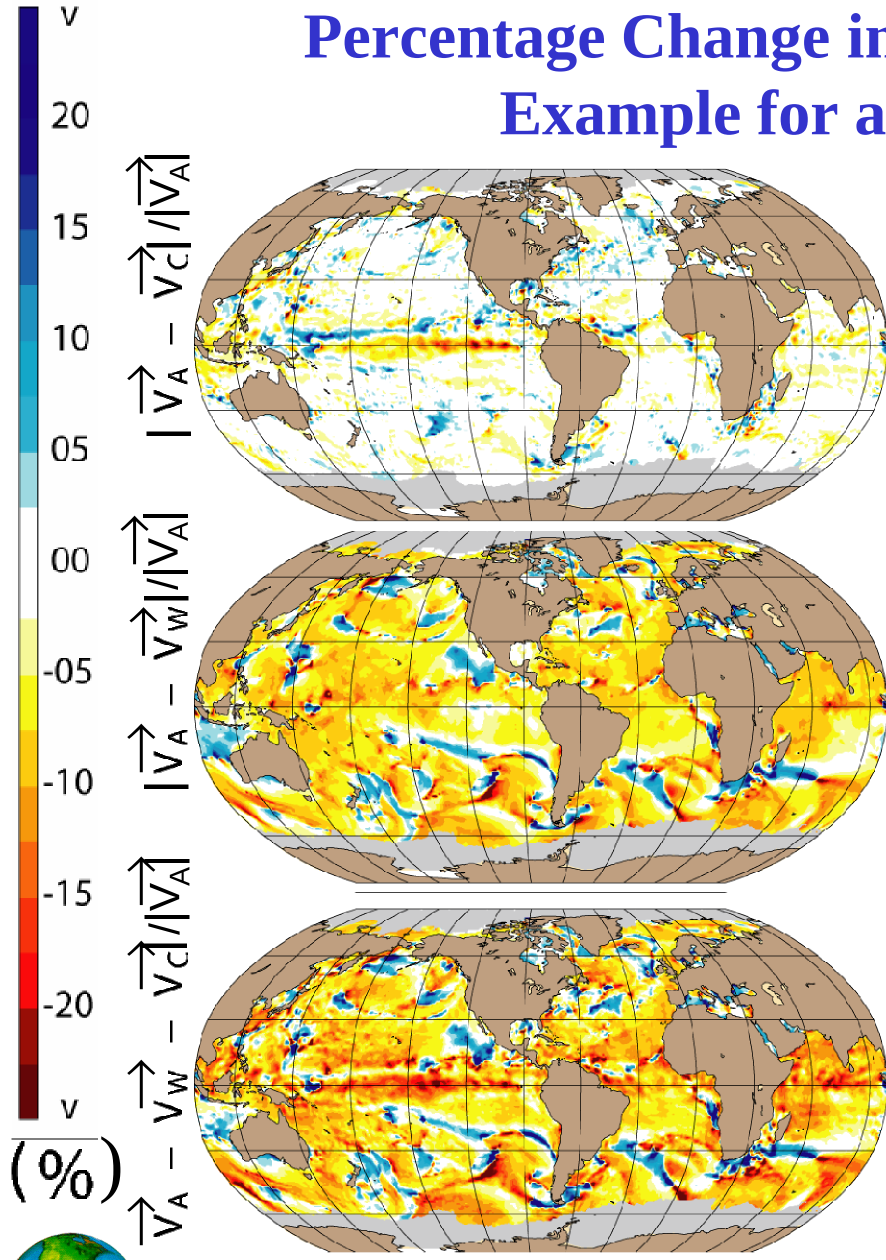
$$\boldsymbol{\tau} = \rho C_D \left|\mathbf{U}_{10}\right| \mathbf{U}_{10}$$

- It can be further improved in terms of surface relative wind vectors:

$$\boldsymbol{\tau} = \rho C_D \left|\mathbf{U}_{10} - \mathbf{U}_{sfc}\right| \left(\mathbf{U}_{10} - \mathbf{U}_{sfc}\right)$$

- Does a scatterometer respond to $\mathbf{U}_{10}$ or to $\mathbf{U}_{10} - \mathbf{U}_{sfc}$?
  - *Cornillon and Park* (2001, *GRL)*, *Kelly et al.* (2001, *GRL*), and *Chelton et al.* (2004, *Science*) showed that scatterometer winds were relative to surface currents.
  - *Bentamy et al.* (2001, *JTech*) indicate there is also a dependence on wave characteristics.
  - *Bourassa* (2006, *WIT Press*) showed that wave dependency can be parameterized as a change in $\mathbf{U}_{sfc}$.
  - Bourassa and Wentz have both find biases related to air density.

Percentage Change in Surface Relative Winds
Example for a 00Z Comparison



- The percentage change in surface relative winds is roughly proportional to the change in energy fluxes.
- The percentage change squared is roughly proportional to changes in stress.
- The drag coefficient also changes
    - >50% changes in stress associated with strong storms!
    - Can have opposite change nearby.
    - Huge change in the curl of the stress!
    - Caveat: models uncoupled!

From *Kara et al.* (2007, *GRL*)

The Log-Wind Profile, and Equivalent Neutral Winds

The dependency of wind speed (U) on the height above the surface (z) is described by a log-wind profile

$$\mathbf{U} - \mathbf{U}_{sfc} = \frac{\mathbf{u}_*}{k}\left[\ln\left(\frac{z}{z_o}+1\right)+\phi\left(z,z_o,L\right)\right]$$

- The friction velocity (u_*) is the squareroot of the kinematic stress: $\tau = \rho u_*^2$
- The ϕ term is a function of atmospheric stratification.
- The 10m Equivalent Neutral wind (U_{10EN}) is calculated by using the value of u_* determined from buoy observations, the corresponding value of z_o, and setting ϕ to zero.

$$U_{10EN} = \frac{u_*}{k}\ln\left(\frac{10}{z_o}\right)$$

What If A Scatterometer Responds to Stress?

- If scatterometers respond in a manner consistent with equivalent neutral winds, then they respond to changes in friction velocity (u_*).

$$U_{10EN} = \frac{u_*}{k} \ln\left(\frac{10}{z_o}\right)$$

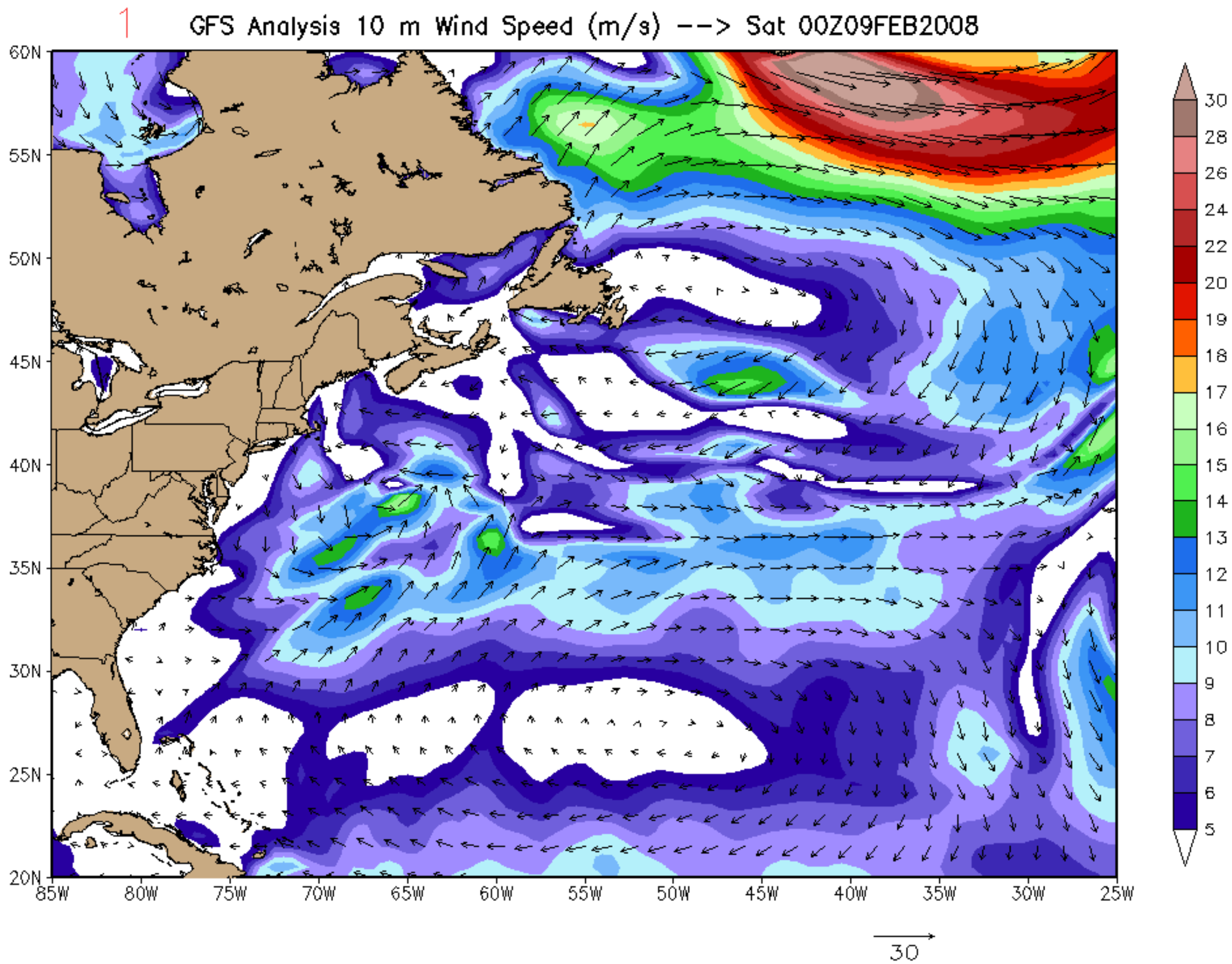
- If scatterometers respond to stress, then it responds to changes in air density and change in friction velocity!
  - The friction velocity (u_*) is the squareroot of the kinematic stress:

$$\tau = \rho_{air}\, u_*^{\,2}$$

$$U_{10EN} = \frac{(\tau / \rho)^{0.5}}{k} \ln(10 / z_o)$$

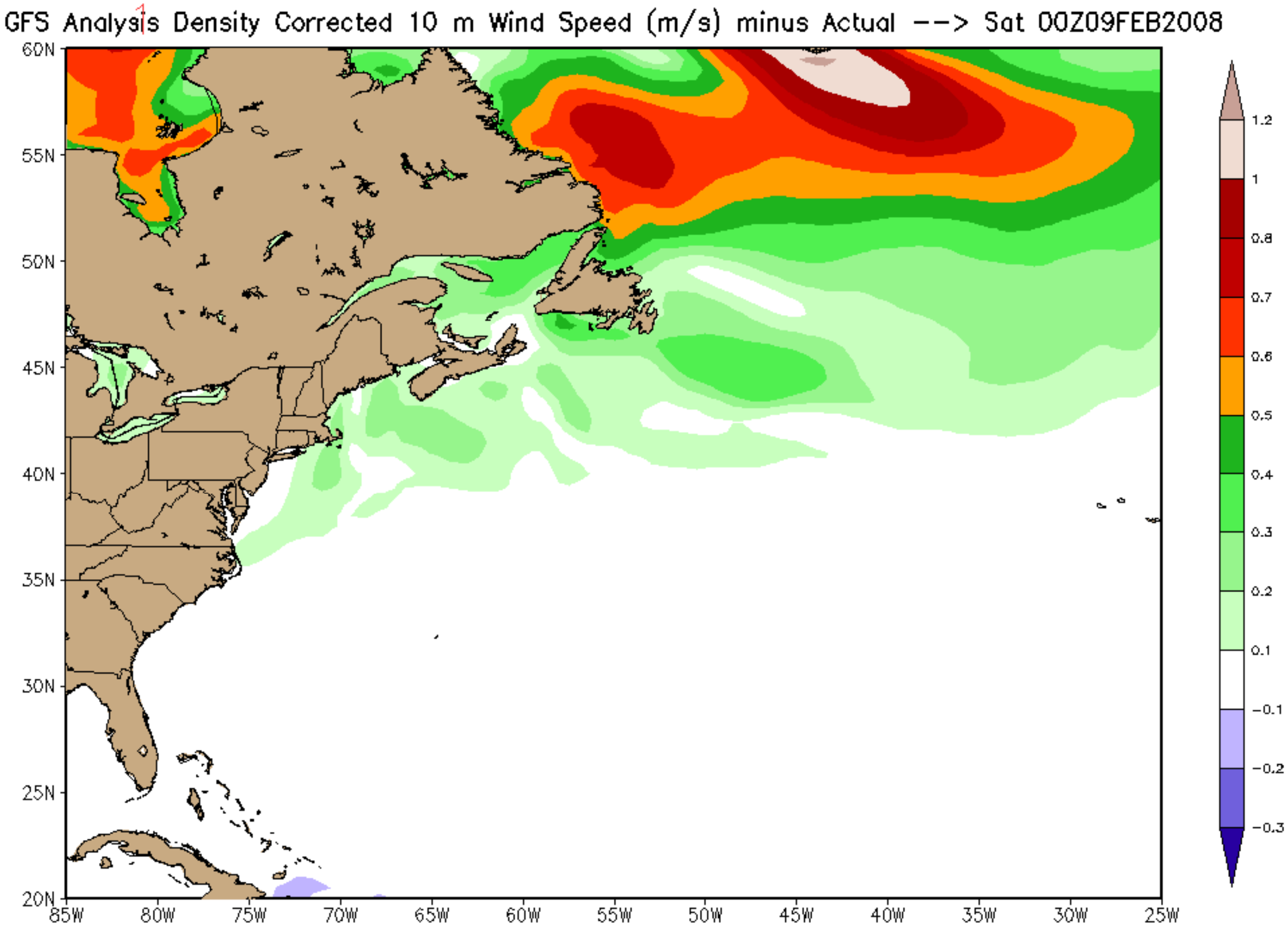
- If scatterometers respond to stress, then calibrations to this form of equivalent neutral winds will be off by a factor of $\rho^{0.5}$,
  - Or more accurately, in proportion to (actual density / mean calibration density)$^{0.5}$

Example: A Cold Air Outbreak



- Example from NCEP’s high resolution model, the GFS analysis.
- 0.5° (~40km) grid spacing
- 10 m wind
- Every 3rd vector

Example: Density-Related Bias in Equiv. Neut. Winds



- Shows overestimate of QSCAT winds.
- $U_{10} - U_{10}\,(\bar{\rho}\,/\,\rho)^{0.5}$
- Density is calculated from GFS 2m values.

Goal & Issues

- Interest: How big are biases in fluxes associated with common assumptions?
  - On what time scales will these biases seriously alter assumptions
- Goal: Assess the influence of synoptic or finer scale variability on LHF
  - That is, differences from fluxes based on monthly averaged inputs
  - Wave-related variability is ignored in this part of the study

Submonthly Contribution to Average LHF

- L is determined through a bulk formula.

  $$L \approx \boxed{\bar{\rho} L_v C_E \bar{U} (\bar{q}_{sfc} - \bar{q})}$$

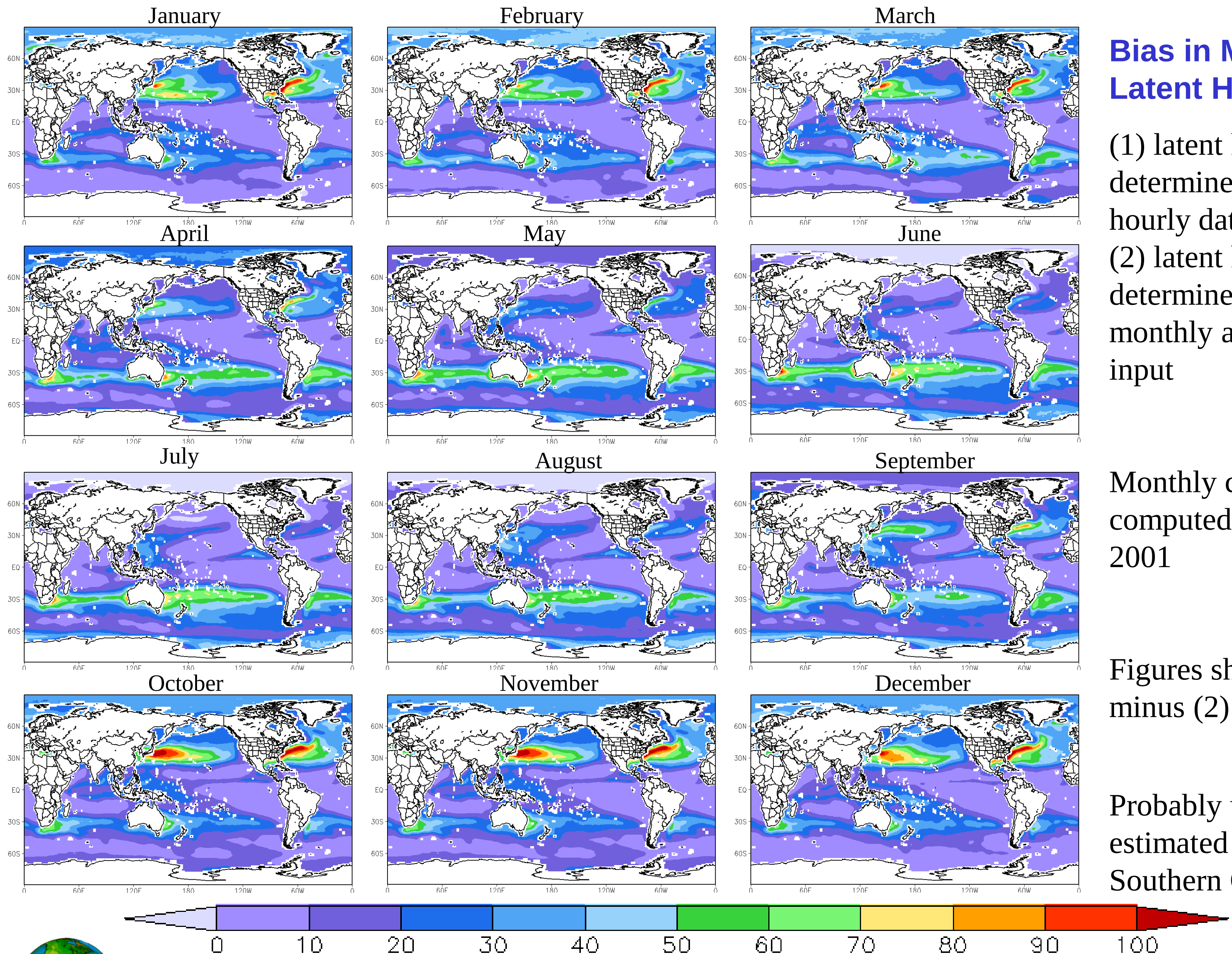
  - Where the overbar indicates a monthly average
  - There is considerable controversy about that accuracy of this averaging
- A more accurate approach is to calculate the flux at each time step then average these fluxes: $L \approx \overline{\rho L_v C_E U (q_{sfc} - q)}$
- If we apply Reynolds averaging this equation becomes

  $$L = \bar{\rho} L_v \overline{\left(\bar{C}_E + C'_E\right)\left(\bar{U} + U'\right)\left(\bar{q}_{sfc} - q'_{sfc} - \bar{q} + q'\right)}$$

- If we assume density variations are not important, this equation becomes

  $$L = \boxed{\bar{\rho} L_v \bar{C}_E \bar{U} (\bar{q}_{sfc} - \bar{q})} + \bar{\rho} L_v \left(\bar{C}_E \overline{U'(q' - q'_{sfc})} + \bar{U}\, \overline{C'_E (q' - q'_{sfc})} + \overline{(q' - q'_{sfc})\, C'_E U'} \right)$$

- Following examples of monthly biases are based on ECMWF reanalysis.
  - Plots bias from using monthly averaged flux input data
  - They do not include wave information



Bias in Latent Heat Flux (Wm^{-2})

Bias in Monthly Latent Heat Flux

(1) latent heat flux determined from 6 hourly data and (2) latent heat flux determined from monthly averaged input

Monthly climatology computed for 1978-2001

Figures show: (1) minus (2)

Probably under-estimated for the Southern Ocean

Mark A. Bourassa

Thanks to Paul Hughes and Ryan Maue

How Do Waves Enter The Picture?

- The surface turbulent stress and LHF are usually parameterized as

$$\tau = \rho C_D U_{10}^2 \qquad\qquad L = \rho L_v C_E (q_{10} - q_{sfc}) U_{10}$$

- This form can be more accurately written as

$$\boldsymbol{\tau} = \rho C_D \left|\mathbf{U}_{10}\right| \mathbf{U}_{10} \qquad\qquad L = \rho L_v C_E (q_{10} - q_{sfc}) \left|\mathbf{U}_{10}\right|$$

- It can be further improved in terms of surface relative wind vectors:

$$\boldsymbol{\tau} = \rho C_D \left|\mathbf{U}_{10} - \mathbf{U}_{sfc}\right| \left(\mathbf{U}_{10} - \mathbf{U}_{sfc}\right) \qquad\qquad L = \rho L_v C_E (q_{10} - q_{sfc}) \left|\mathbf{U}_{10} - \mathbf{U}_{sfc}\right|$$

- Does a scatterometer respond to $\mathbf{U}_{10}$ or to $\mathbf{U}_{10} - \mathbf{U}_{sfc}$?
  - *Cornillon and Park* (2001, *GRL)*, *Kelly et al.* (2001, *GRL*), and *Chelton et al.* (2004, *Science*) showed that scatterometer winds were relative to surface currents.
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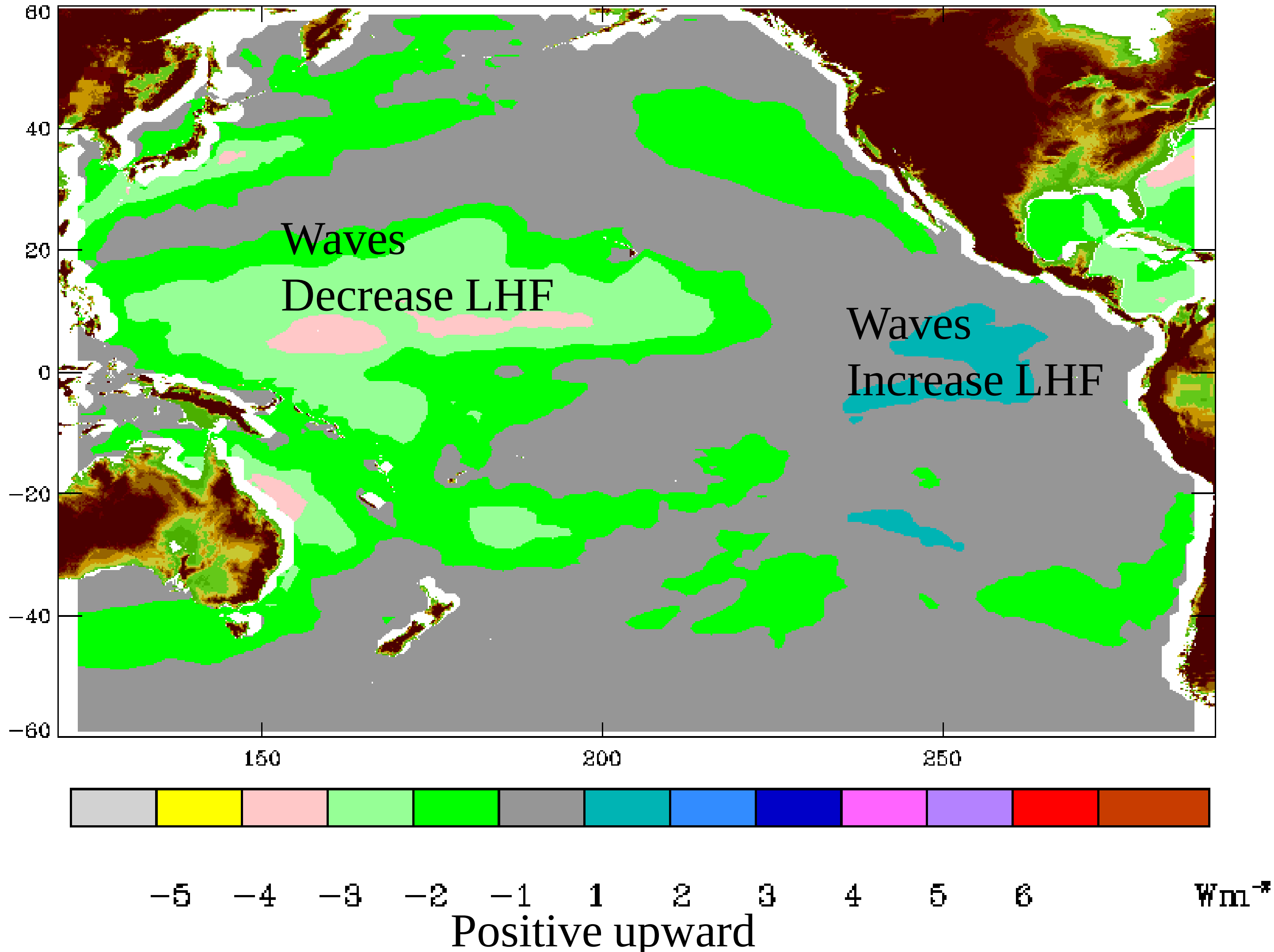
Caveats

- Wave portion of analysis is based on theory – observations and not sufficient
- The one thing flux modeler agree on is that they disagree on how to model wave influence
  - There is a wide range of proposed mechanisms for how waves modify surface fluxes.
- Flux models used to study waves
  - Model used herein is Bourassa (2006):
  - Bourassa, M. A., 2006, Satellite-based observations of surface turbulent stress during severe weather, Atmosphere - Ocean Interactions, Vol. 2., ed., W. Perrie, Wessex Institute of Technology Press, Southampton, UK, 35 – 52 pp.
  - Moisture roughness length based on surface renewal theory: Clayson-Fairall-Curry (1996) model.

Example of Results
Change in LHF Due to Waves: March 1999



Summary

- Scatterometers do seem to respond to stress rather than kinematic stress (equivalent neutral winds) or earth-relative winds.
- Small regional and seasonal biases in the traditional U_{10EN} related to the near-surface air density.
- Conversion of the existing geophysical model function for winds to a model function for stress requires considerations of non-linear terms in the tuning.
- Might be able to estimate stress with better signal to noise ratio than for wind retreivals.

Summary

- Synoptic scale variability in regional latent heat fluxes and flux related variables can be large (>50 Wm^{-2} in some regions).
  - Particularly down wind of continents and by western boundary currents.
  - Implies heat fluxes in the Southern Ocean will be underestimated
- In the tropics, sub-monthly variability - **ignoring waves** – can exceed 20Wm^{-2}; however, it is typically <10 Wm^{-2}.
- Monthly averaged tropical **wave related** variability is more wide spread:
  - Tends to reduce LHF by roughly 5Wm^{-2} in the Western tropical Pacific Ocean
  - Slightly increases LHF in the Eastern tropical Pacific Ocean
  - Could be of interest on ENSO time scales and longer.
- Similar magnitude and spatial distribution to what some people call the global warming signal.

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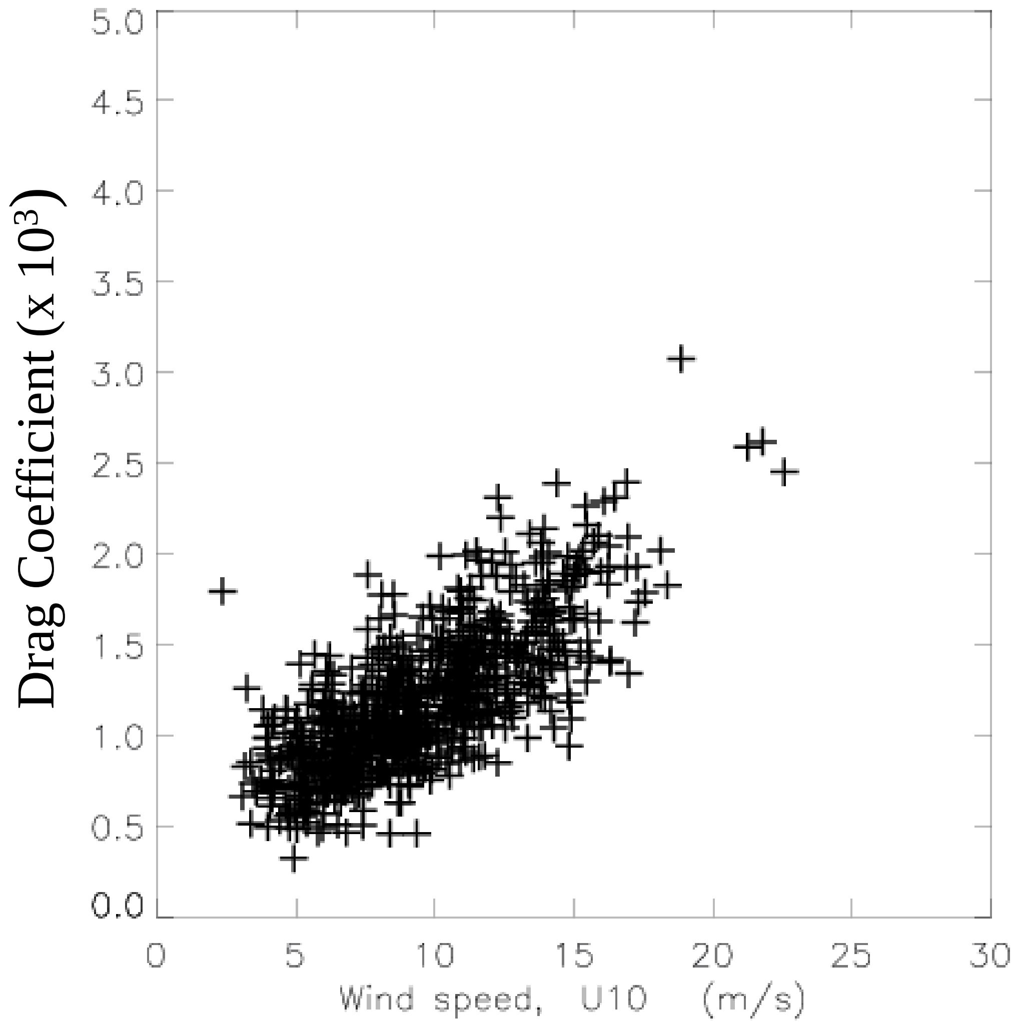
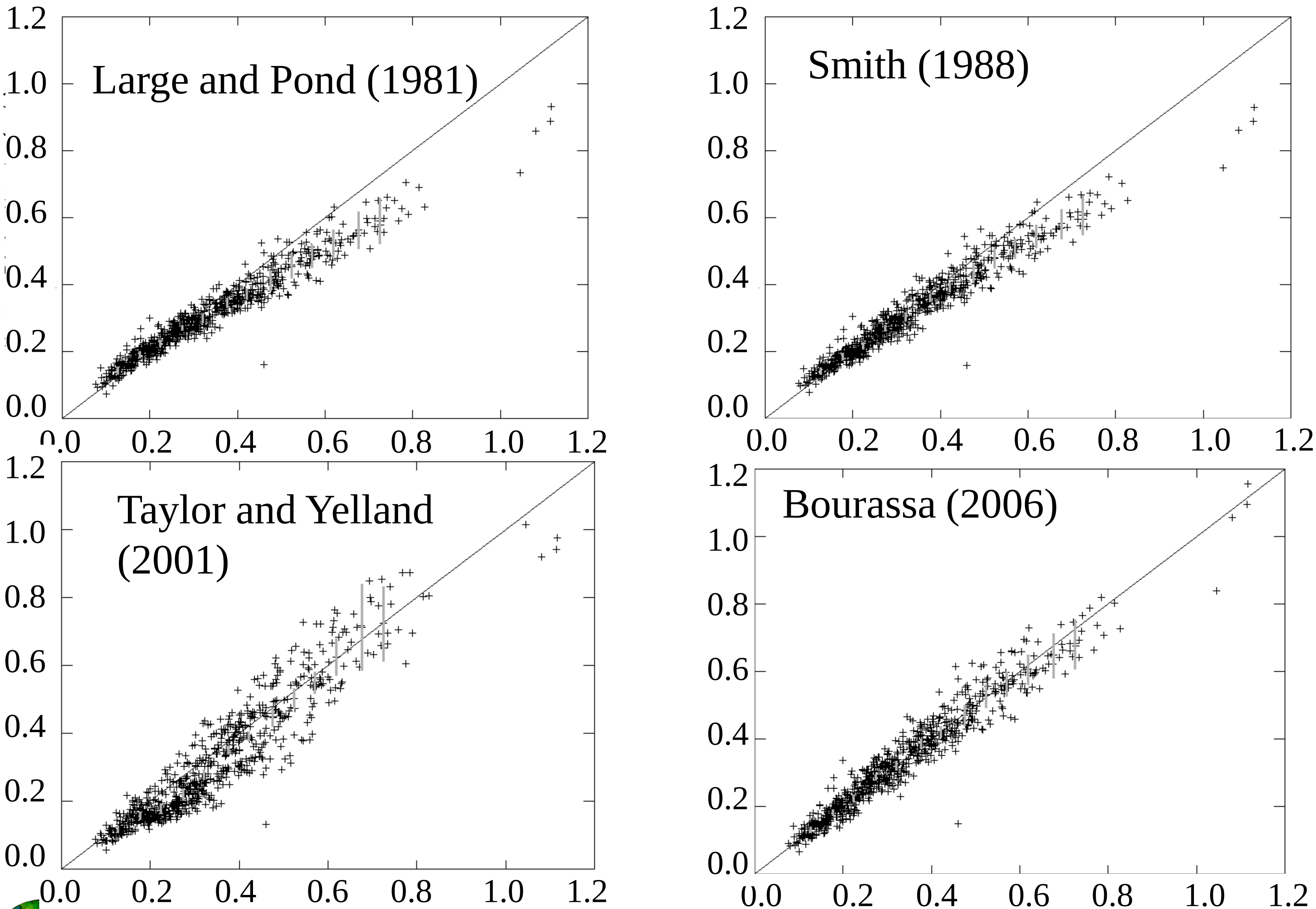
Drag Coefficient vs. Wind Speed

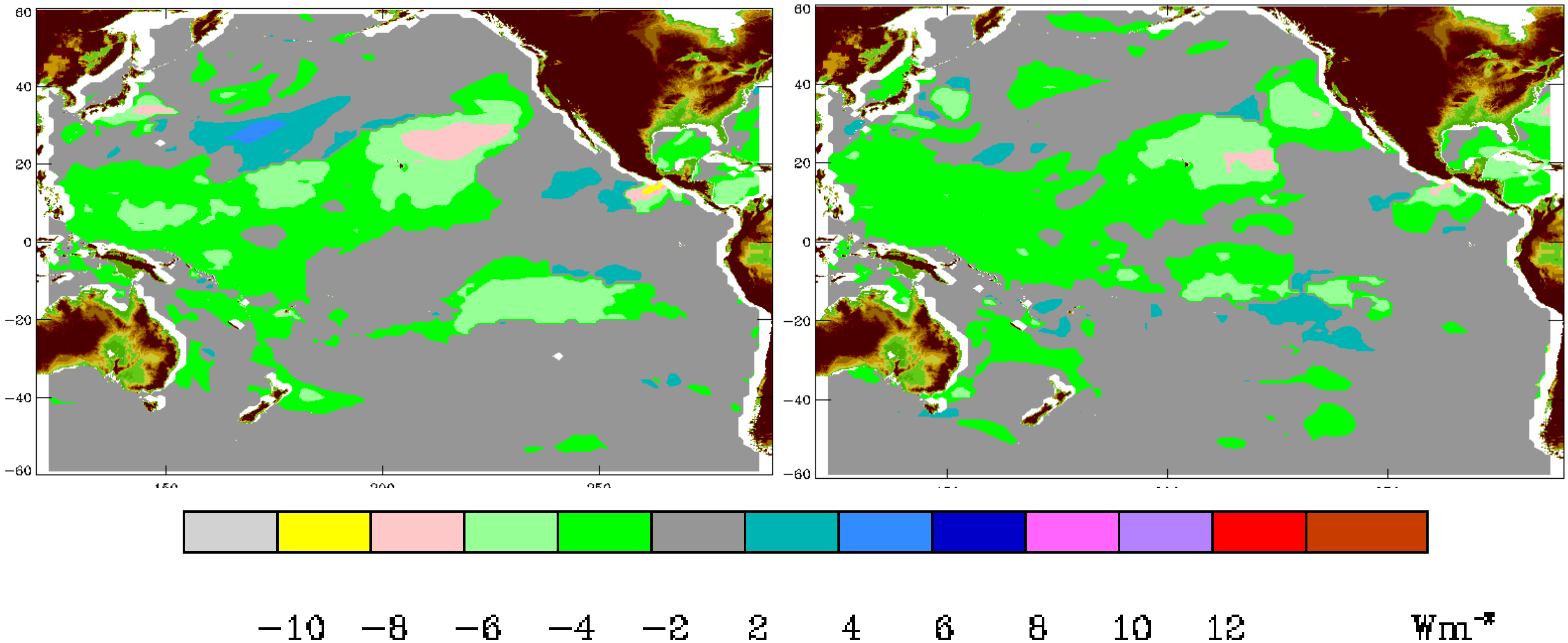


- Preliminary data form the SWS2 (Severe Wind Storms 2) experiment.
  - The drag coefficients for high wind speeds are large and plentiful.
  - The atypically large drag coefficients are associated with rising seas
- Many models underestimate these fluxes.
- Spread is much bigger than expected from observational errors

Observed (x) and Modeled (y) Friction Velocity (u_*)

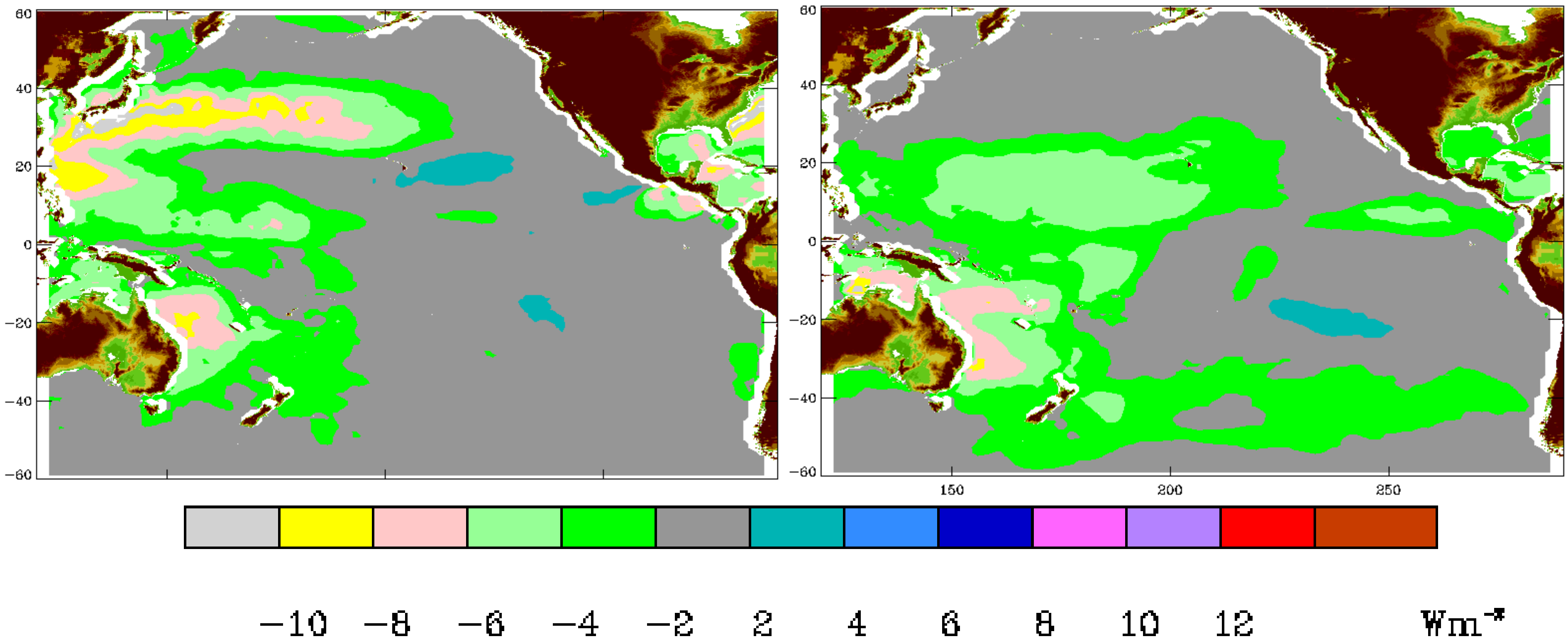


Wave Induced Changes in LHF



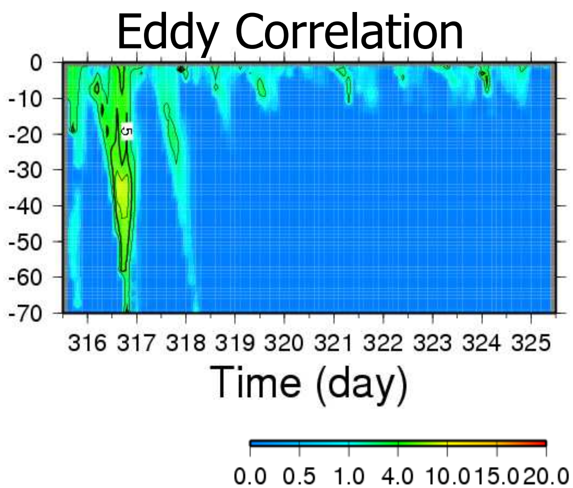
- Examples from snapshots (6 hourly time steps)
- Input data:
  - WaveWatch3 (WW3) winds and waves
  - ECWMF temperatures and humidities

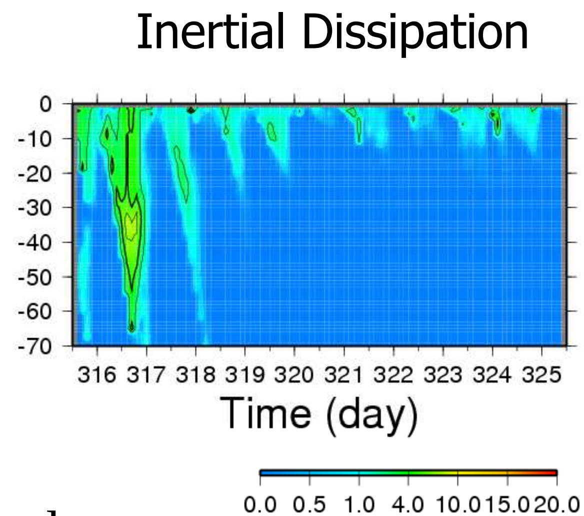
Monthly Averaged Changes in LHF: Two Examples

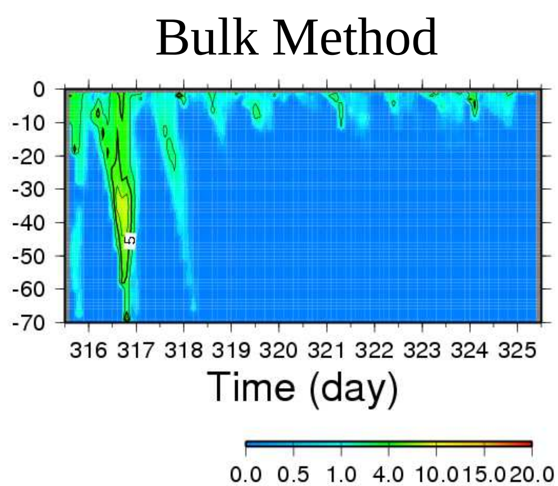


- January 2003 (left) and June 1999 (right)
- One persistent feature is a reduction of heat transfer from the western Pacific warm pool to the atmosphere
- The roughly 5Wm^{-2} across basin difference is important for studies of decadal variability, and possibly for ENSO

Ocean's TKE Based on Observed Surface Fluxes







Calculations by Derrick Weitlich

Clayson & Kantha model