An investigation of the stability dependence of SST-induced vertical mixing over the ocean in the operational Met Office model

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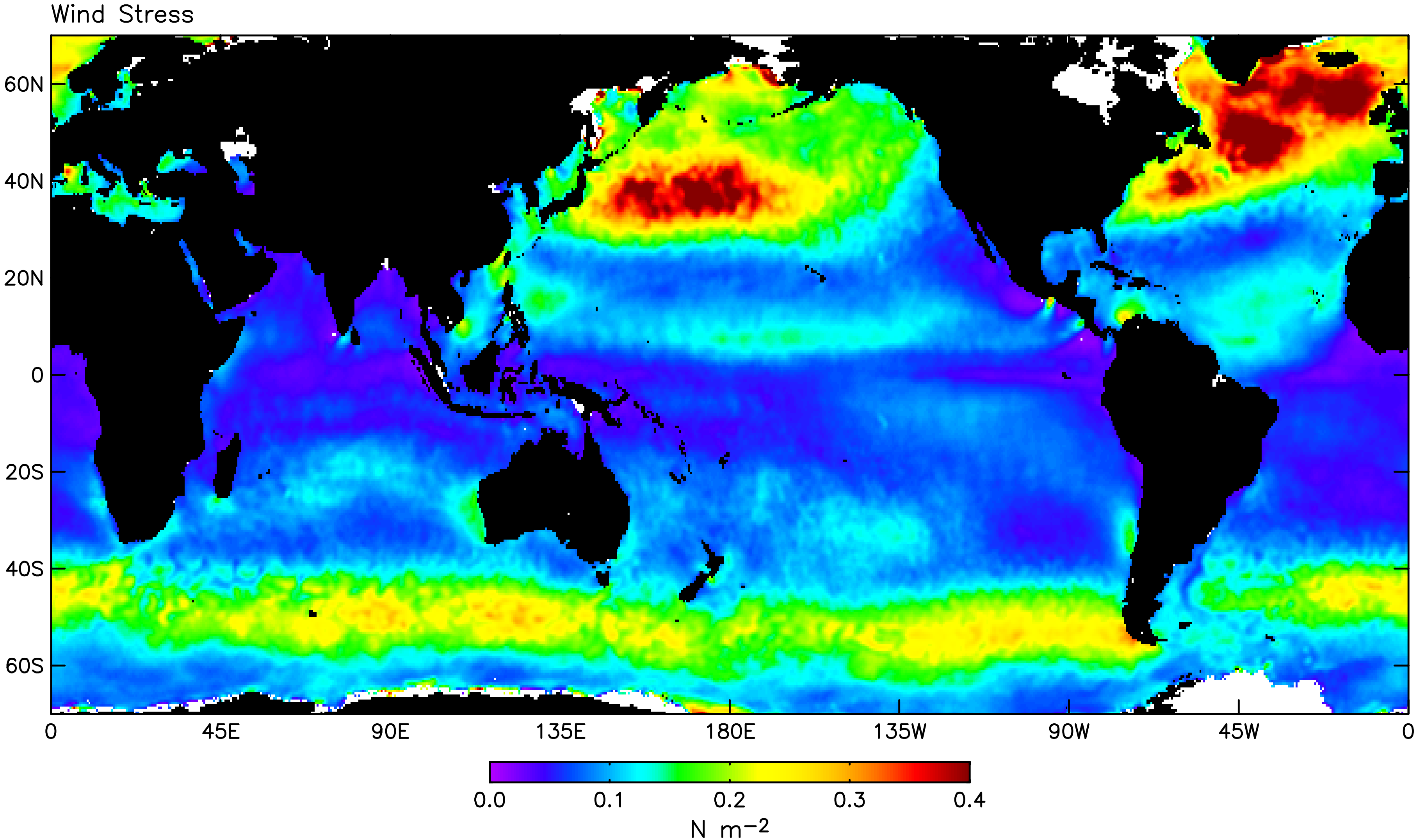
Overview:

- Satellite observations numerical modeling of SST influence on sea surface winds
- Semi-analytical analysis of the UKMO planetary boundary layer parameterizations
- 1-D WRF simulations versus UKMO PBL results
- Summary

2-Month Average Wind Stress Magnitude

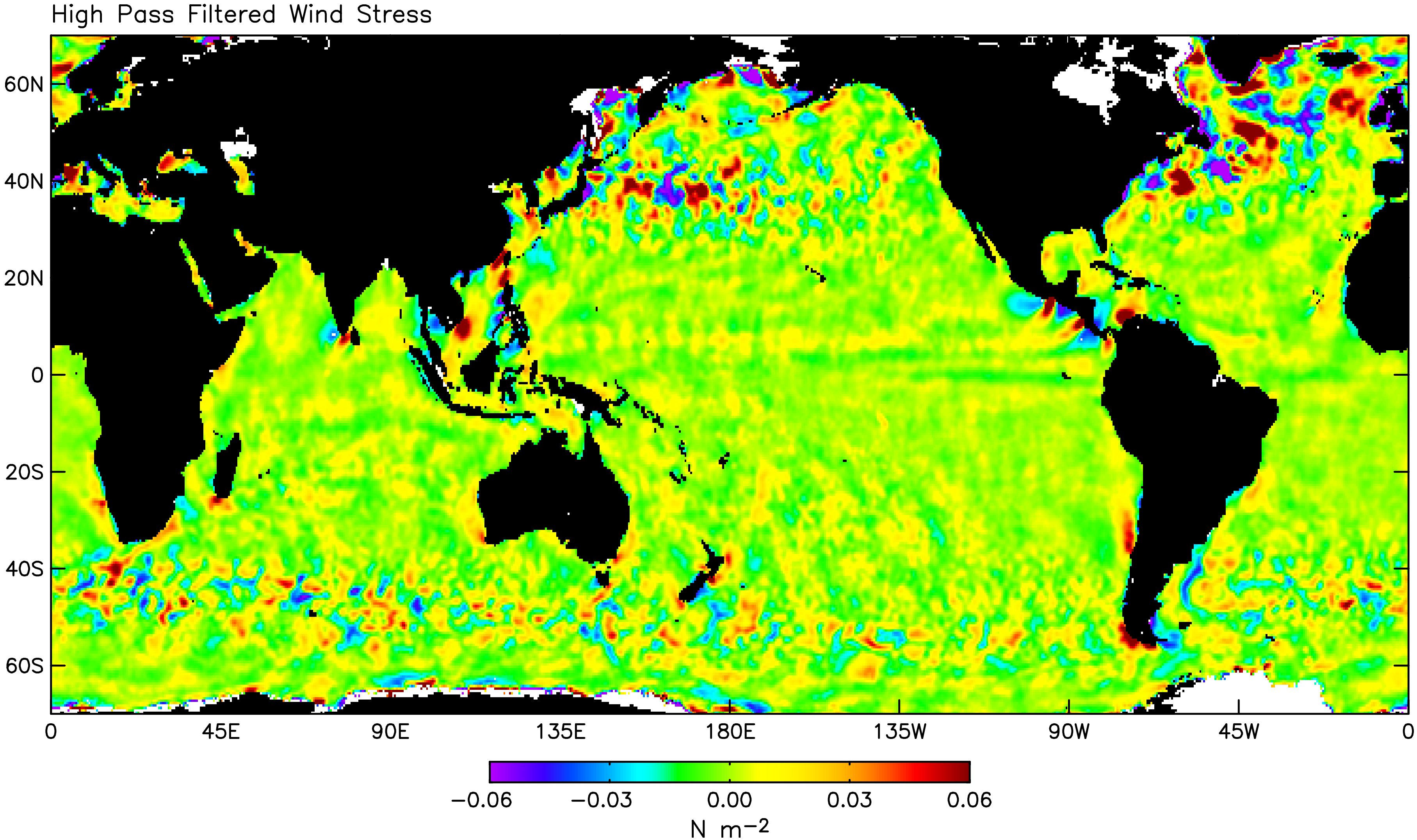
QuikSCAT, January—February 2003



2-Month Average Wind Stress Magnitude

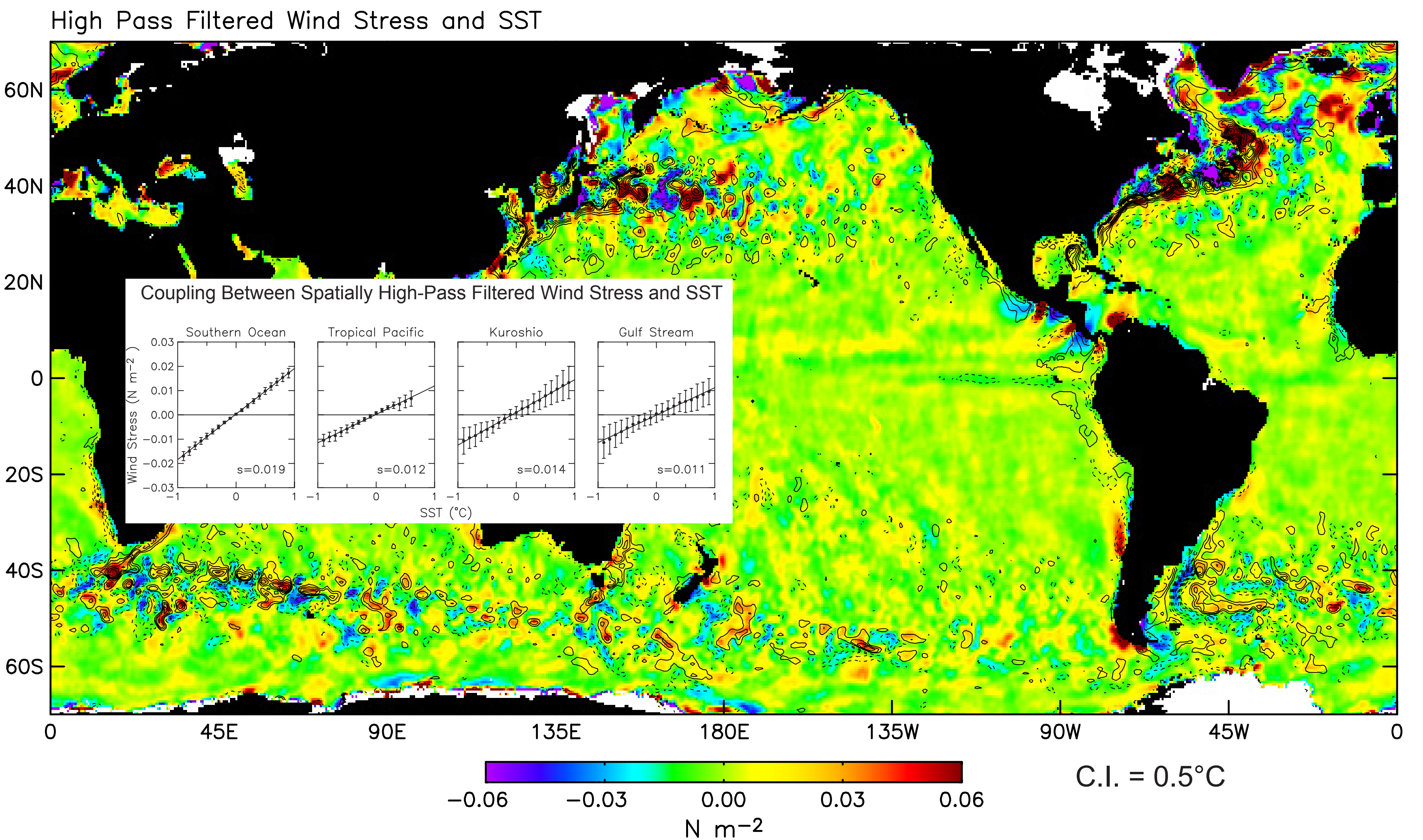
(Spatially High-Pass Filtered)

QuikSCAT, January–February 2003



2-Month Average Wind Stress Magnitude and SST
(Spatially High-Pass Filtered)

QuikSCAT, January–February 2003



2-Month Average Wind Stress Magnitude and SST
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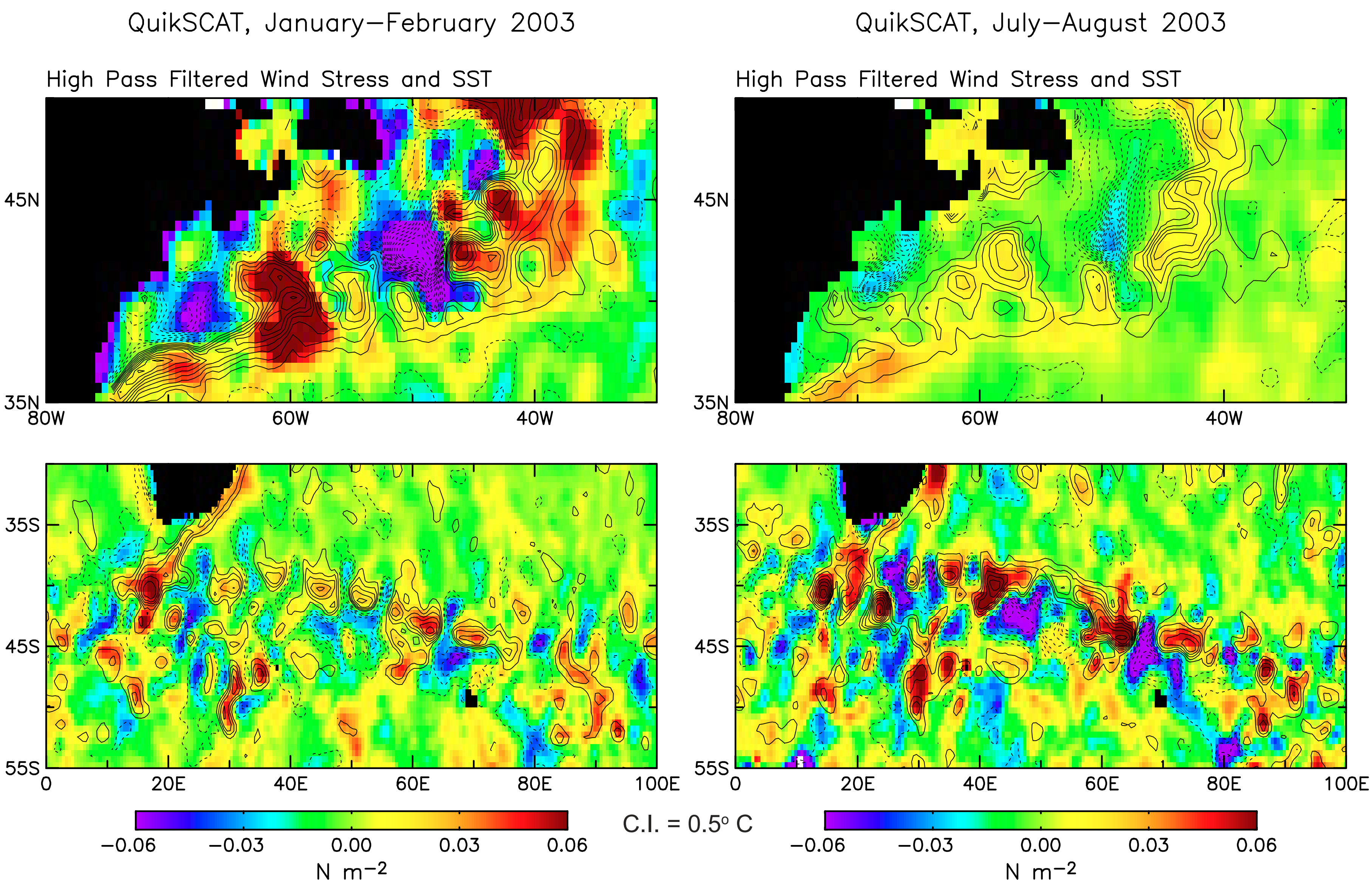
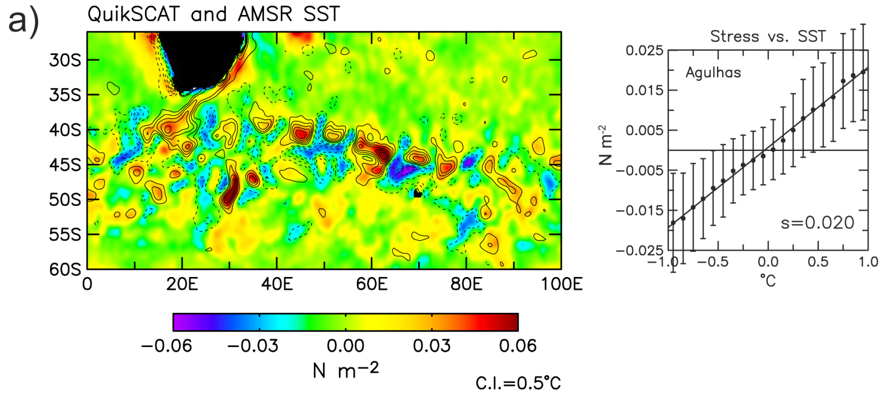
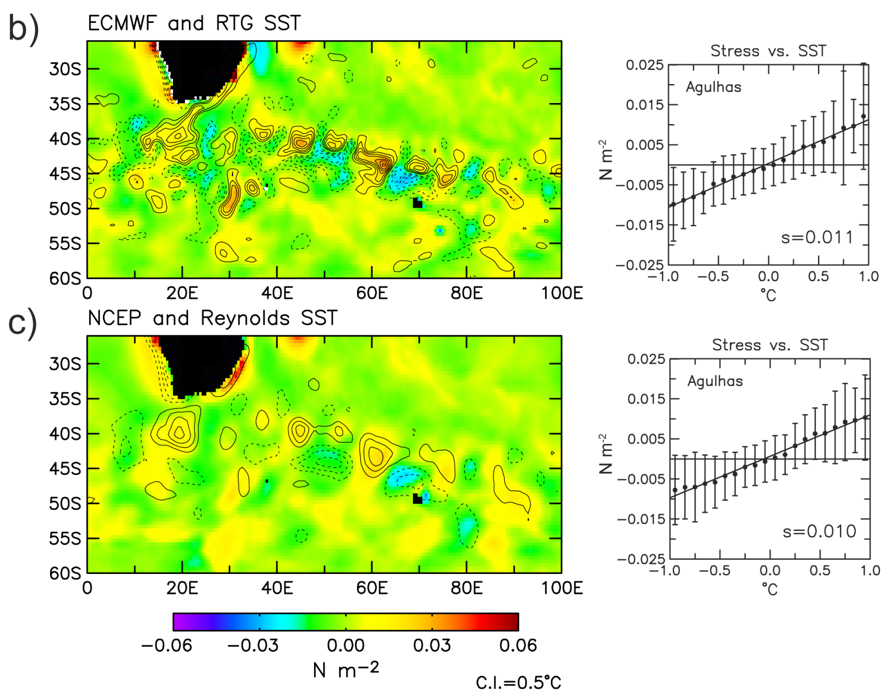


Agulhas Return Current (Southwest Indian Ocean)

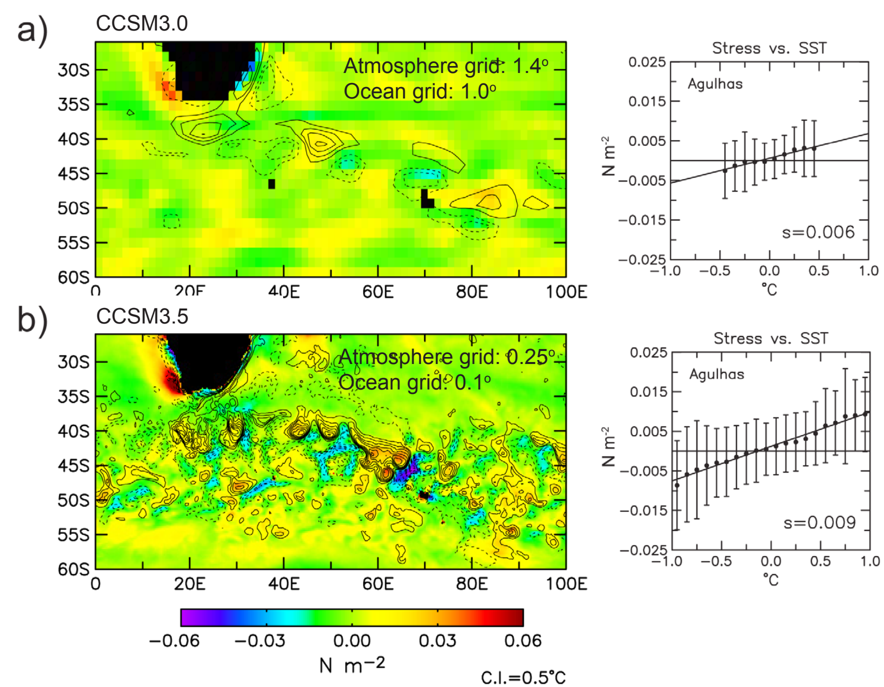
Satellite Observations



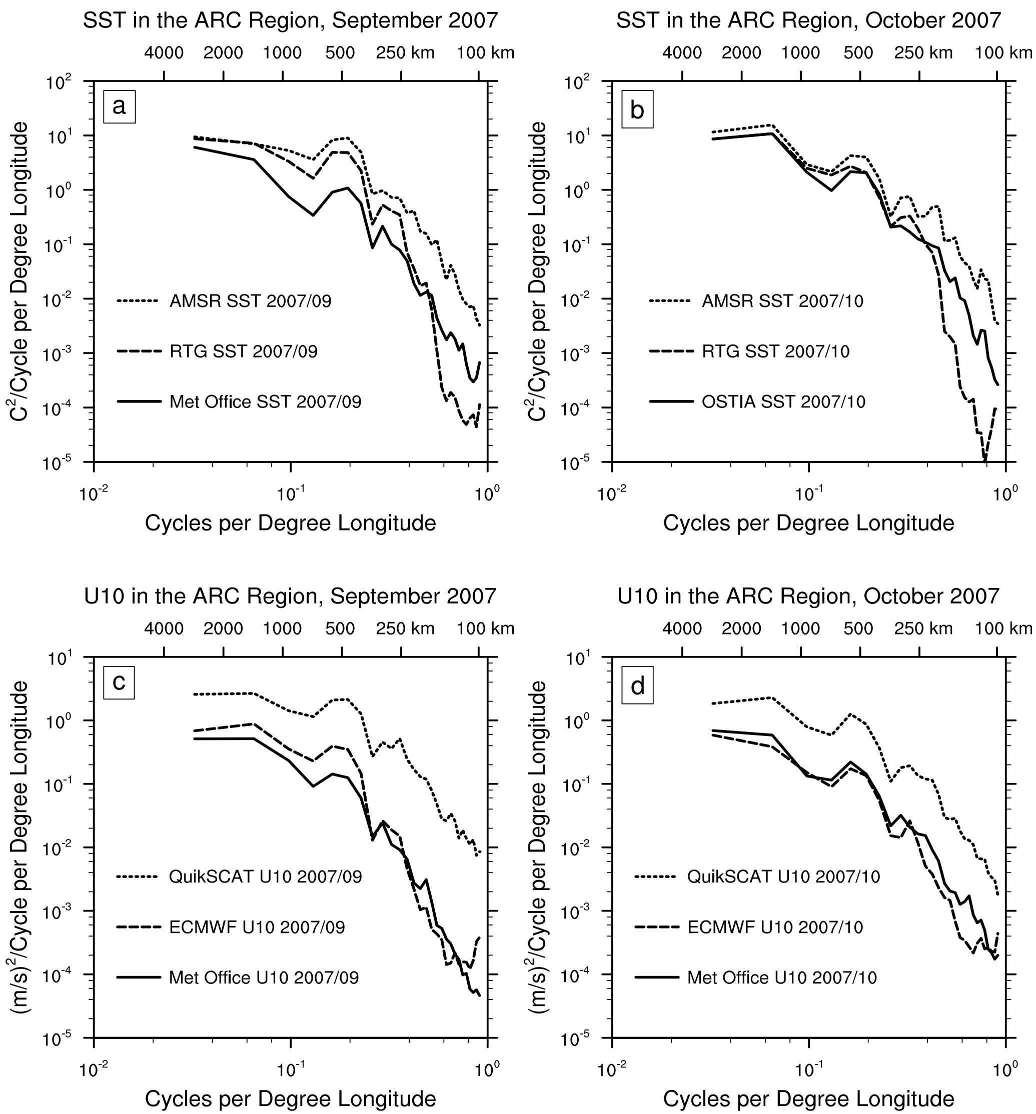
Operational Weather Forecast Models



NCAR Coupled Climate Models



Power Spectral Densities of SST and Wind Speed



March 2007: UKMO change of vertical mixing to non-local.

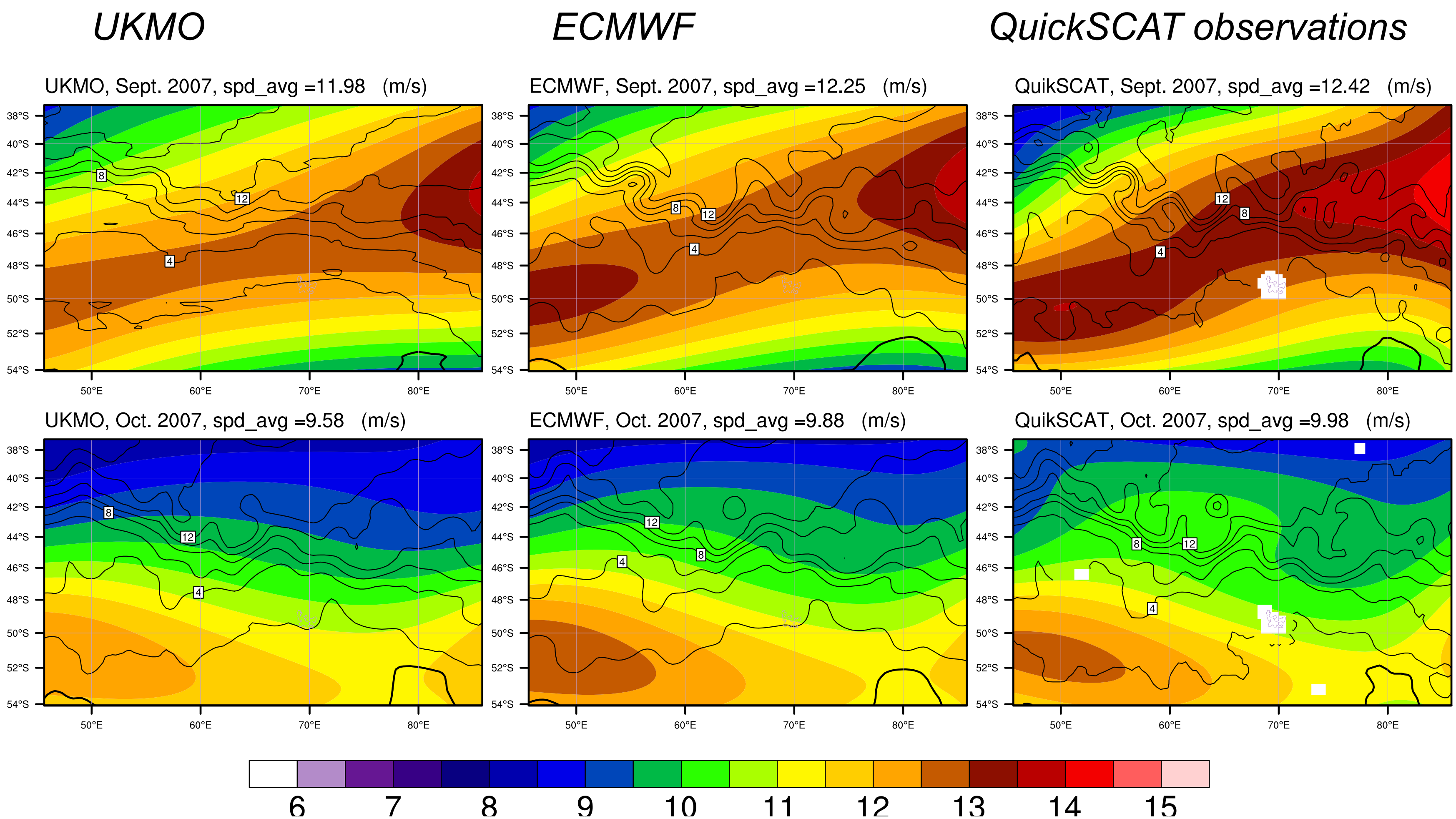
October 2007: SST boundary conditions change from Met Office SST to OSTIA.

Objectives:

1. to determine if the March 2007 change improved air-sea coupling.

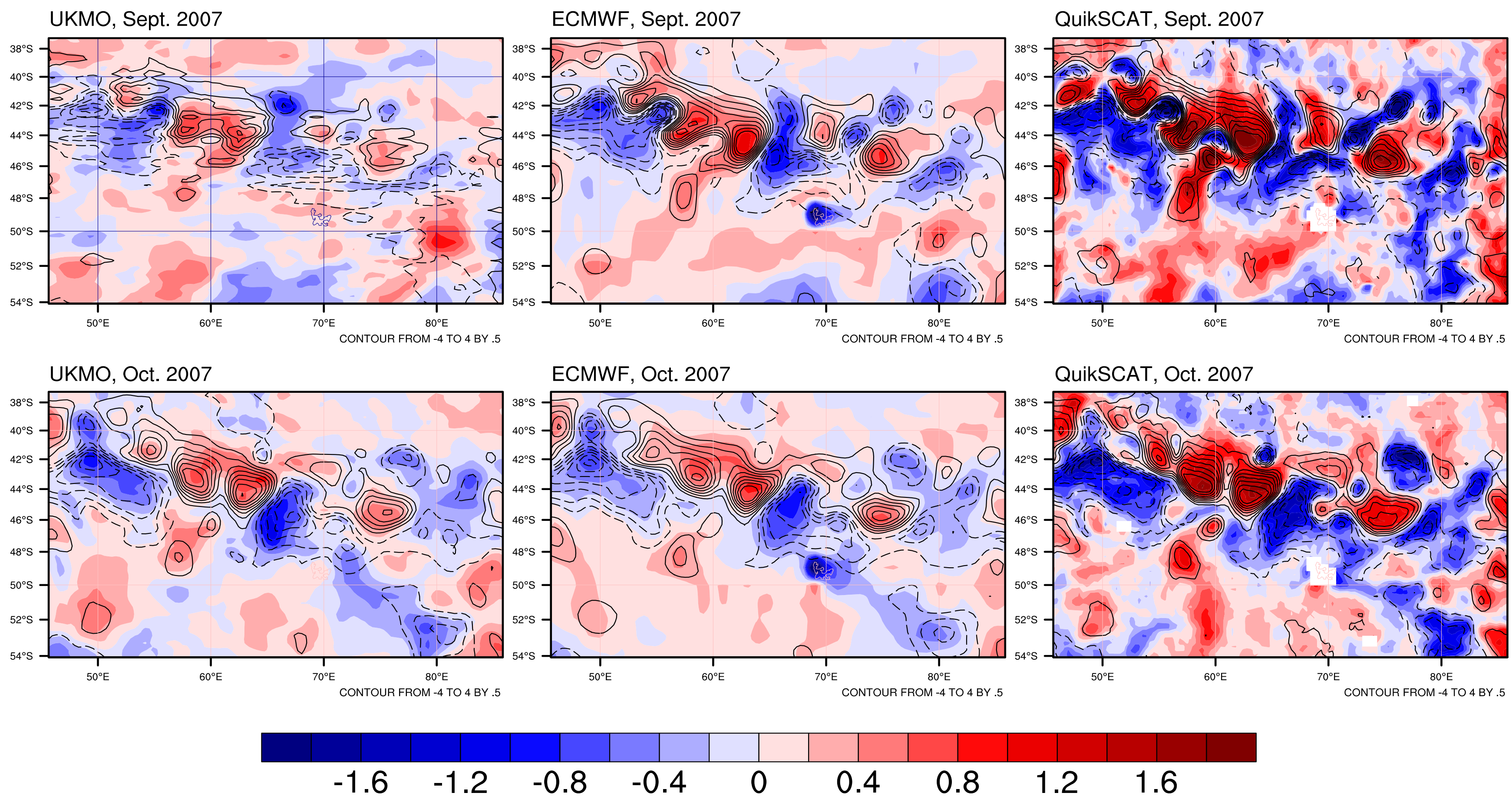
2. to investigate the possible reasons for improvements, if any.

Maps of spatially low-pass filtered wind speed and SST



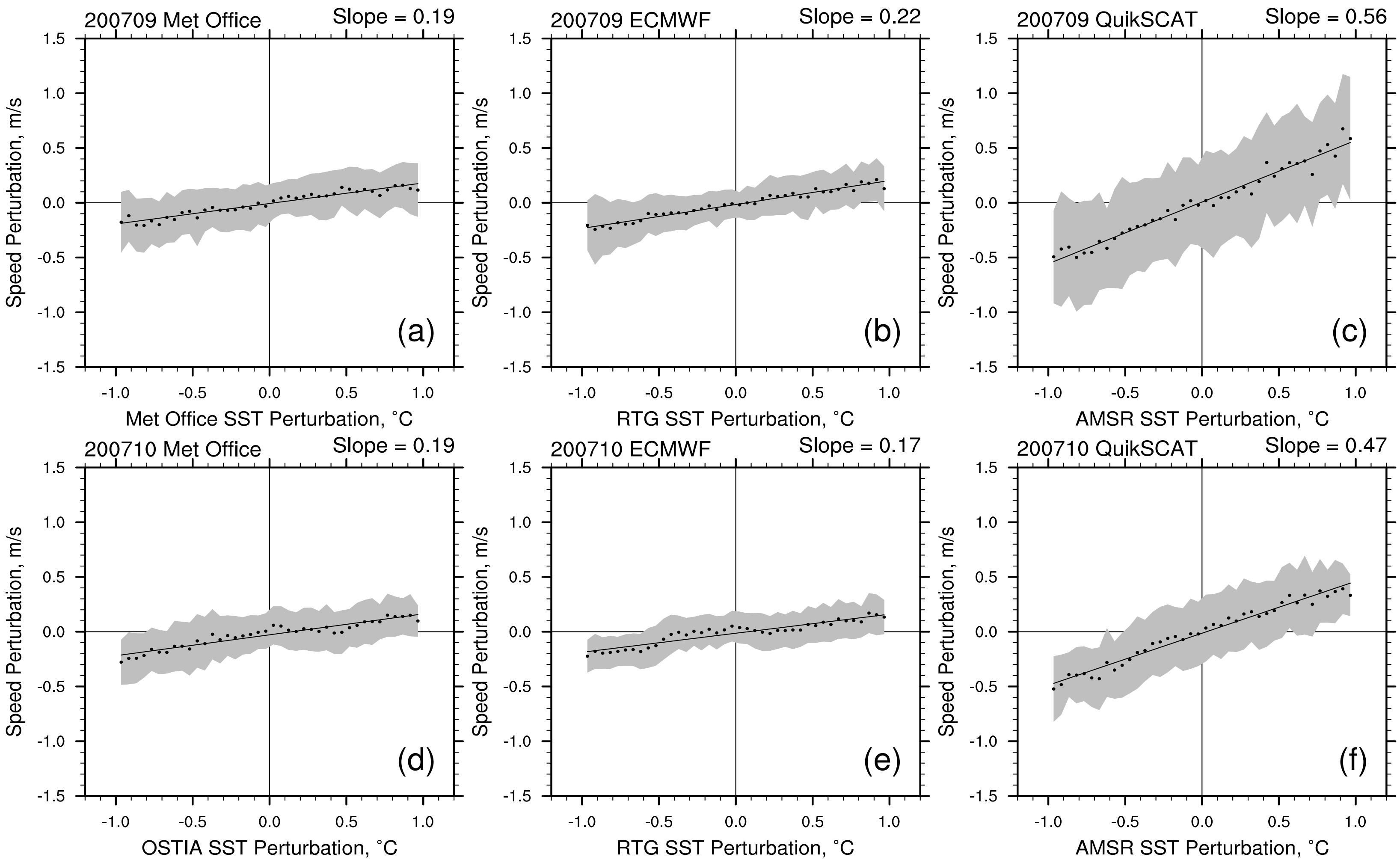
Maps of spatially high-pass filtered wind speed and SST

UKMO *ECMWF* *QuickSCAT observations*



Wind-SST coupling coefficient, 2007 in the Southern Ocean

UKMO *ECMWF* *QuickSCAT observations*



The UKMO parameterizations of vertical mixing in the planetary boundary layer

Briefly, the total turbulent flux is parameterized as the sum of contributions from local mixing and nonlocal mixing:

$$\overline{u'w'} = \overline{u'w'}_{local} + \overline{u'w'}_{NL}\,, \tag{1}$$

where u' and w' are the horizontal and vertical eddy velocities, respectively. Both contributions are implemented throughout the marine atmospheric boundary layer (MABL). The local mixing term is given by

$$\overline{u'w'}_{local} = -K_m \frac{\partial u}{\partial z}\,. \tag{2}$$

The eddy diffusivity, K_m, is parameterized within the boundary layer as

$$K_m = w_m \kappa z \left(1 - \frac{z}{z_i}\right)^2\,, \tag{3}$$

where w_m is a velocity scale, κ is the von Karman constant, z is the height above the sea surface, and z_i is the height of the top of the MABL. The local mixing then becomes

$$\overline{u'w'}_{local} = -w_m u_* \left(1 - \frac{z}{z_i}\right)^2 , \tag{4}$$

Near the sea surface ($z < 0.1z_i$), the velocity scale is set to $w_m = [u_*^3 + 2.5(z/z_i)w_*^3]^{1/3}$, where w_* is the convective velocity scale that characterizes the boundary layer stability and is defined as

$$w_* = \left[\frac{gz_i}{\overline{\theta_v}}\left(\overline{w'\theta_v{}'}\right)_s\right]^{1/3} , \tag{5}$$

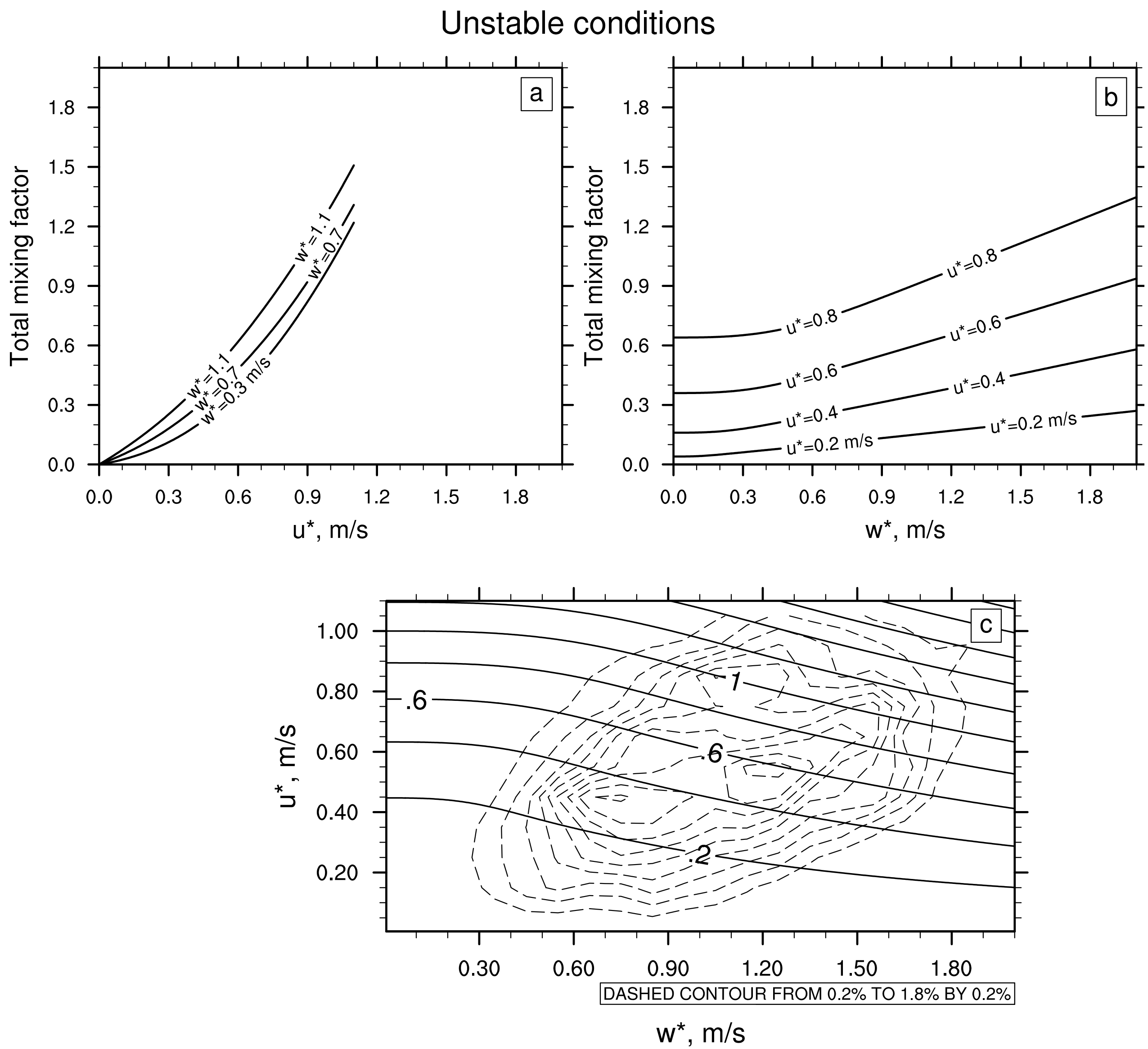
where $(g/\overline{\theta_v})(\overline{w'\theta_v{}'})_s$ is the surface buoyancy flux for gravitational acceleration g and potential temperature θ_v that consists of a large-scale component $\overline{\theta_v}$ and an eddy component $\theta_v{}'$. The local momentum mixing near the sea surface can then be written as

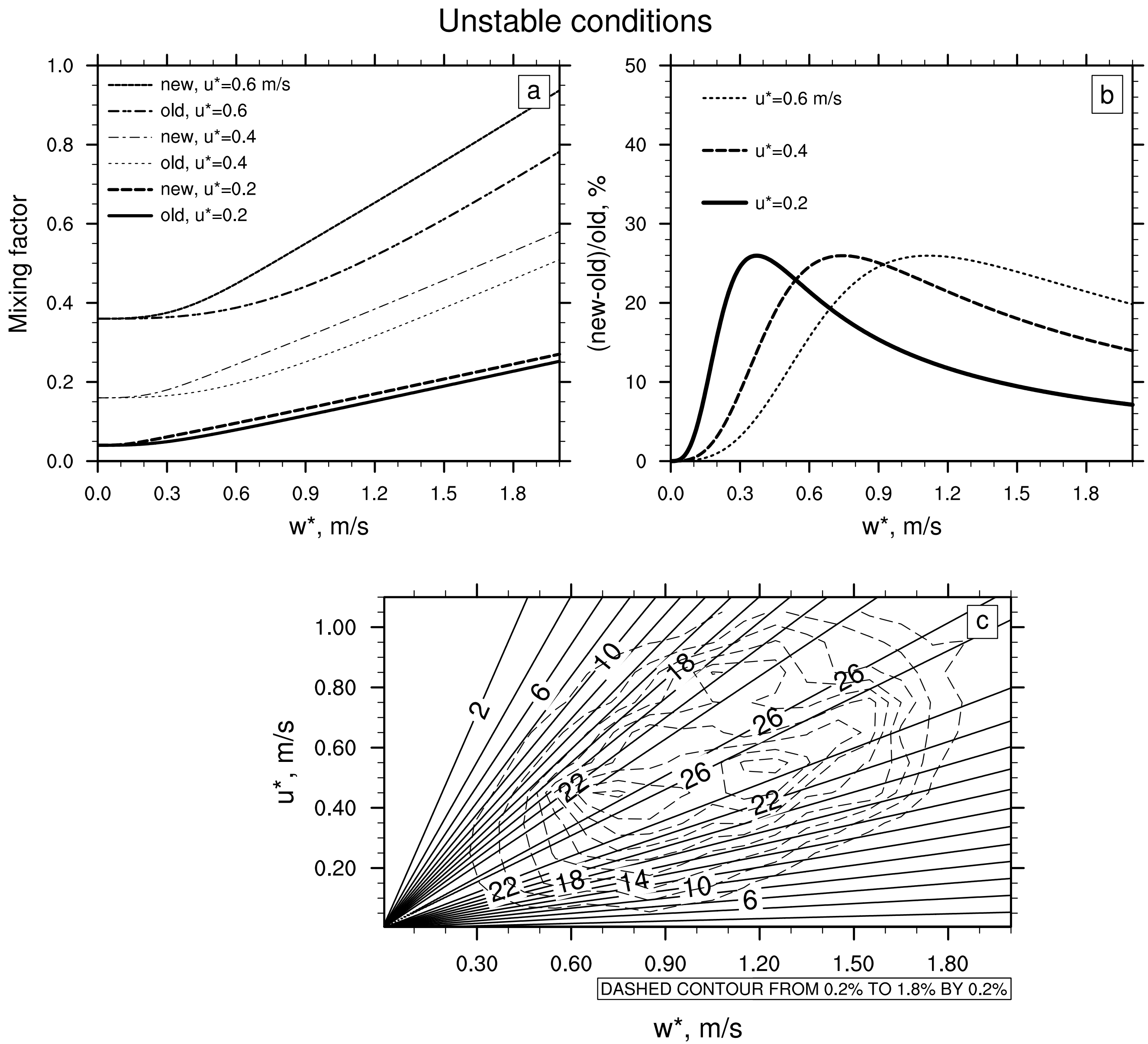
$$\overline{u'w'}_{local} = -u_* \left(u_*^3 + 2.5\frac{z}{z_i}w_*^3\right)^{1/3} \left(1 - \frac{z}{z_i}\right)^2 . \tag{6}$$

The magnitude of the total vertical momentum flux in Eq. (1) obtained by substituting Eq. (6) for the local mixing term $\overline{u'w'}_{local}$ and Eq. (3) of Brown et al. (2006) for the non-local mixing term $\overline{u'w'}_{NL}$ has the form

$$\left|\overline{u'w'}\right| = \left[u_* \left(u_*^3 + 2.5\frac{z}{z_i}w_*^3\right)^{1/3} + u_*^2 \frac{2.7w_*^3}{u_*^3 + 0.6w_*^3}\left(\frac{z}{z_i}\right)\right]\left(1 - \frac{z}{z_i}\right)^2. \quad (7)$$

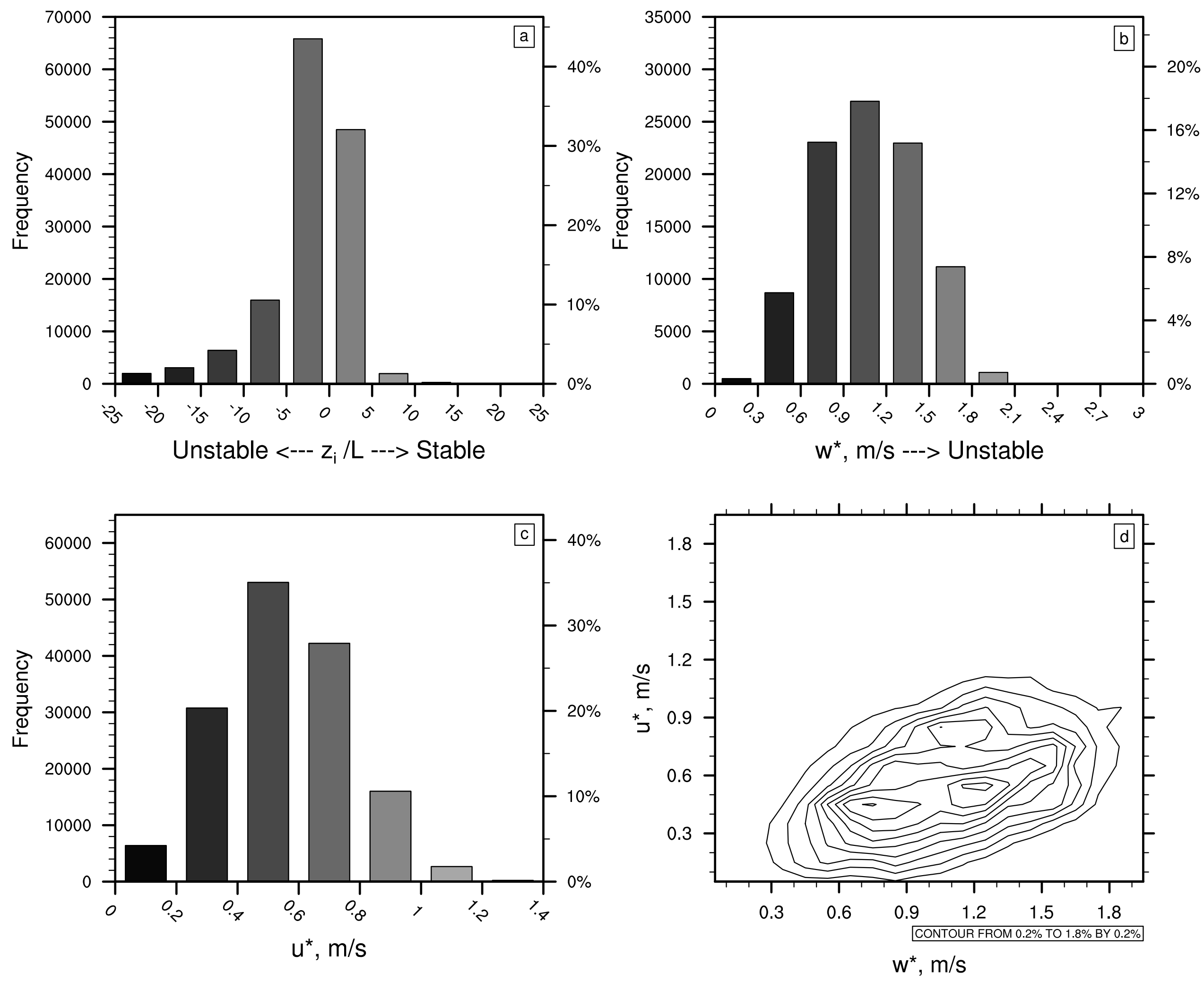
Next slide: the dependencies of this total vertical momentum mixing on stability (characterized by w*) and surface wind speed (characterized by u*)


Unstable conditions
a
Total mixing factor
u*, m/s
w*=1.1
w*=0.7
w*=0.3 m/s
0.0
0.3
0.6
0.9
1.2
1.5
1.8
b
Total mixing factor
w*, m/s
u*=0.8
u*=0.6
u*=0.4
u*=0.2 m/s
c
u*, m/s
w*, m/s
1.00
0.80
0.60
0.40
0.20
0.30
0.60
0.90
1.20
1.50
1.80
1
.6
.2
DASHED CONTOUR FROM 0.2% TO 1.8% BY 0.2%



Unstable conditions
a
new, u*=0.6 m/s
old, u*=0.6
new, u*=0.4
old, u*=0.4
new, u*=0.2
old, u*=0.2
Mixing factor
1.0
0.8
0.6
0.4
0.2
0.0
0.0 0.3 0.6 0.9 1.2 1.5 1.8
w*, m/s
b
u*=0.6 m/s
u*=0.4
u*=0.2
(new-old)/old, %
50
40
30
20
10
0
0.0 0.3 0.6 0.9 1.2 1.5 1.8
w*, m/s
c
u*, m/s
1.00
0.80
0.60
0.40
0.20
2
6
10
18
26
26
26
22
22
22
18
14
10
6
0.30 0.60 0.90 1.20 1.50 1.80
DASHED CONTOUR FROM 0.2% TO 1.8% BY 0.2%
w*, m/s

Histograms of -z_i/L, w*, and u* from UKMO model simulations



3. One-dimensional WRF simulation versus UKMO PBL results

WRF GBM PBL, released in WRF version 3.5, April, 2013.

- *Grenier and Bretherton, 2001, Mon. Wea. Rev.*
- *Grenier and Bretherton, 2004, J. of Climate*
- *Qingtao Song, Dudley Chelton, Steve Esbensen, 2009, J. of Climate*
- *Natalie Perlin, 2012.*

To make a direct comparison, the single-column WRF model was set up the same as the LES model considered by UKMO PBL

- *a constant geostrophic wind speed of 10 m s^{-1}*
- *a boundary layer height of 1000 m*
- *a roughness length z_0 = 0.0001 m representative of boundary layer conditions over the ocean*

Modification of the Grenier and Bretherton (2001) Parameterization of Vertical Mixing for these Sensitivity Studies

The Grenier and Bretherton (2001) parameterization enhances the vertical transport of TKE to match the TKE profile obtained from large-eddy simulations by formulating the vertical eddy diffusivity as

$$K_m = Q_m l \sqrt{e}$$

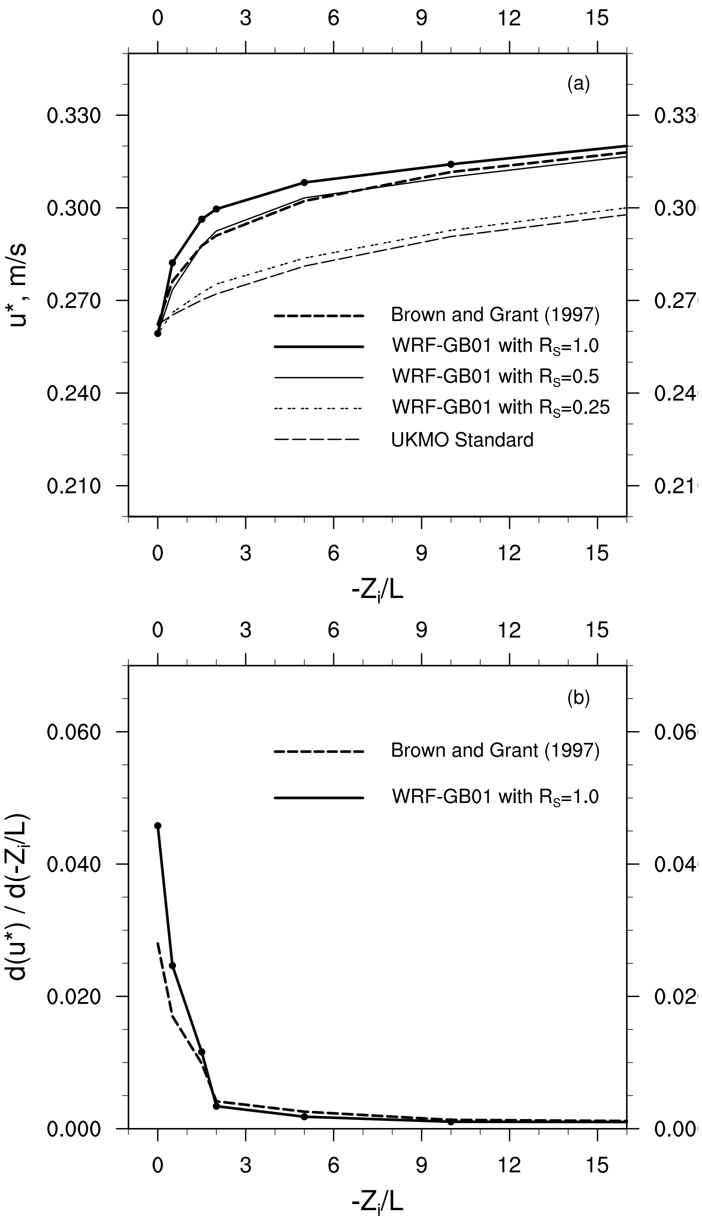
where Q_m is 5 times larger than the Mellor-Yamada mixing.

This stability dependence is modified here to have the form

$$Q_m = S_m^N + R_s \left(5S_m - S_m^N\right),$$

where S_m^N is the stability function for neutrally static conditions and the stability response factor R_s modulates the dependence of vertical diffusion on stability.

A value of $R_s = 1$ corresponds to the Grenier and Bretherton (2001) scheme. Values of $R_s < 1$ correspond to reduced dependence of vertical mixing on stability.



Dependence of u on stabillity parameter $-z_i/L$*

Thick dashed line: the LES results with non-local mixing described in Brown and Grant (1997).

Solid lines: 1-D WRF simulations with different stability response factors Rs.

*Dependence of rate of change of frictional velocity u*on stabillity parameter $-z_i/L$*

Conclusions

- *SST exerts a strong influence on surface winds. OSTIA SST analyses are far superior to the old UKMO SST fields*

- *The parameterization of vertical mixing in the surface layer appears to hold the key to understanding the discrepancies between modeled and observed surface wind response to SST.*

- *For unstable conditions, the 1-D WRF simulations indicate that the UKMO mixing sensitivity to stability is only about half of what is required to represent the satellite observations of surface wind speed response to SST*.*

- *Further enhancements of vertical mixing beyond that of the UKMO BG97 parameterization are required in the weak-to-moderately unstable conditions in order for the UKMO and ECMWF models to represent the surface wind response to SST accurately.*

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