The Stokes drift and wave induced-mass flux in the North Pacific

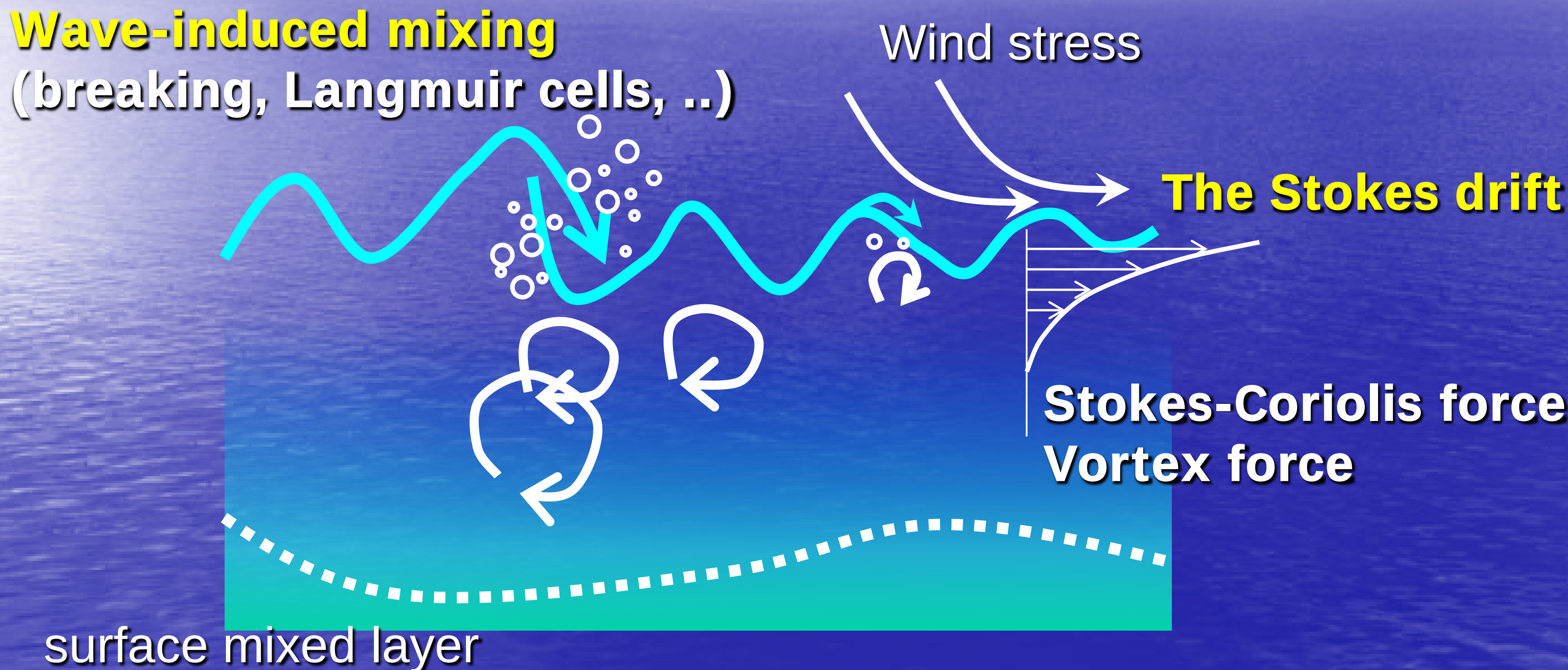
Hitoshi Tamura[1], Lakshmi Kantha[2]
Yasumasa Miyazawa[1], and Leo Oey[3]

1. Research Institute for Global Change, JAMSTEC, Japan
2. Department of Aerospace Eng. Sciences, U. Colorado, Boulder, USA
3. Program in Atmos. and Ocean Science, Princeton Univ., USA

Tamura et al (2012, JGR -Oceans)
Kantha et al (2013, JGR-Oceans submitted)

Motivations

Ocean waves have significant impacts on upper ocean processes



Explicit evaluation of wave effect is crucial for OGCM and coupled models

Methodology

Ocean wave hindcasts in the Pacific

↓

The Stokes drift and
wave induced-mass flux (wave momentum)

- The Stokes drift in the Pacific
- Parameterization of the Stokes drift
- LES forcing parameters
- Impact of the WMF on the Ekman transport
- Mixing (Non-wave breaking)

Summary and conclusions

- The Stokes drift strongly depends on spectral shape.
- In the Pacific Ocean, the Stokes drift is mainly confined near the surface and the Stokes depth scale is of the order of the significant wave height.
- The div./conv. of wave induced-mass flux is significantly modified by local fetch, the coast and ocean currents.
- For the application of wave-current coupling processes to OGCM, it is clear that high vertical resolution is required to accurately represent the Stokes drift field.

The Stokes drift (linear waves for deep sea)

Stokes drift for <u>**random directional waves**</u> (Kenyon, 1969)

Statistically stationary and spatially homogeneous

$$\overline{\boldsymbol{u}}^{St}(z)=\frac{2}{g}\iint \sigma^{3}F(f,\theta)(\cos\theta,\sin\theta)\cdot\exp(2kz)dfd\theta$$

$\overline{\boldsymbol{u}}^{St}(z)=\overline{\boldsymbol{u}}^{L}-\overline{\boldsymbol{u}}^{E}$ (e.g., Phillips, 1977)

Wave induced-mass flux in Eulerian coordinate is equal to the Stokes transport (depth-integrated Stokes drift);

$$\boldsymbol{M}^{w}=\rho\int_{-\infty}^{\overline{\zeta}}\overline{\boldsymbol{u}}^{St}(z)dz\sim\rho\int_{-D_S^*}^{\overline{\zeta}}\overline{\boldsymbol{u}}^{St}(z)dz$$

The stokes e-folding depth

Ocean wave hindcasts in the Pacific

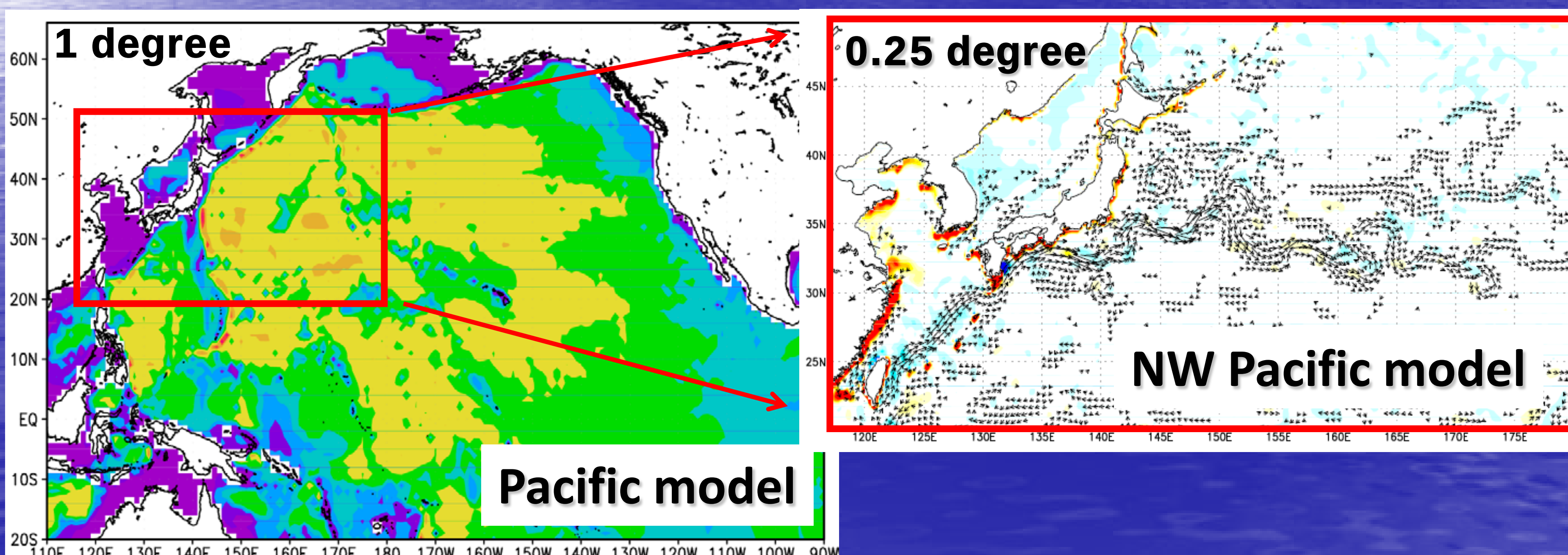
Third generation wave model (WAVEWATCH-III™)

Spectral resolution:

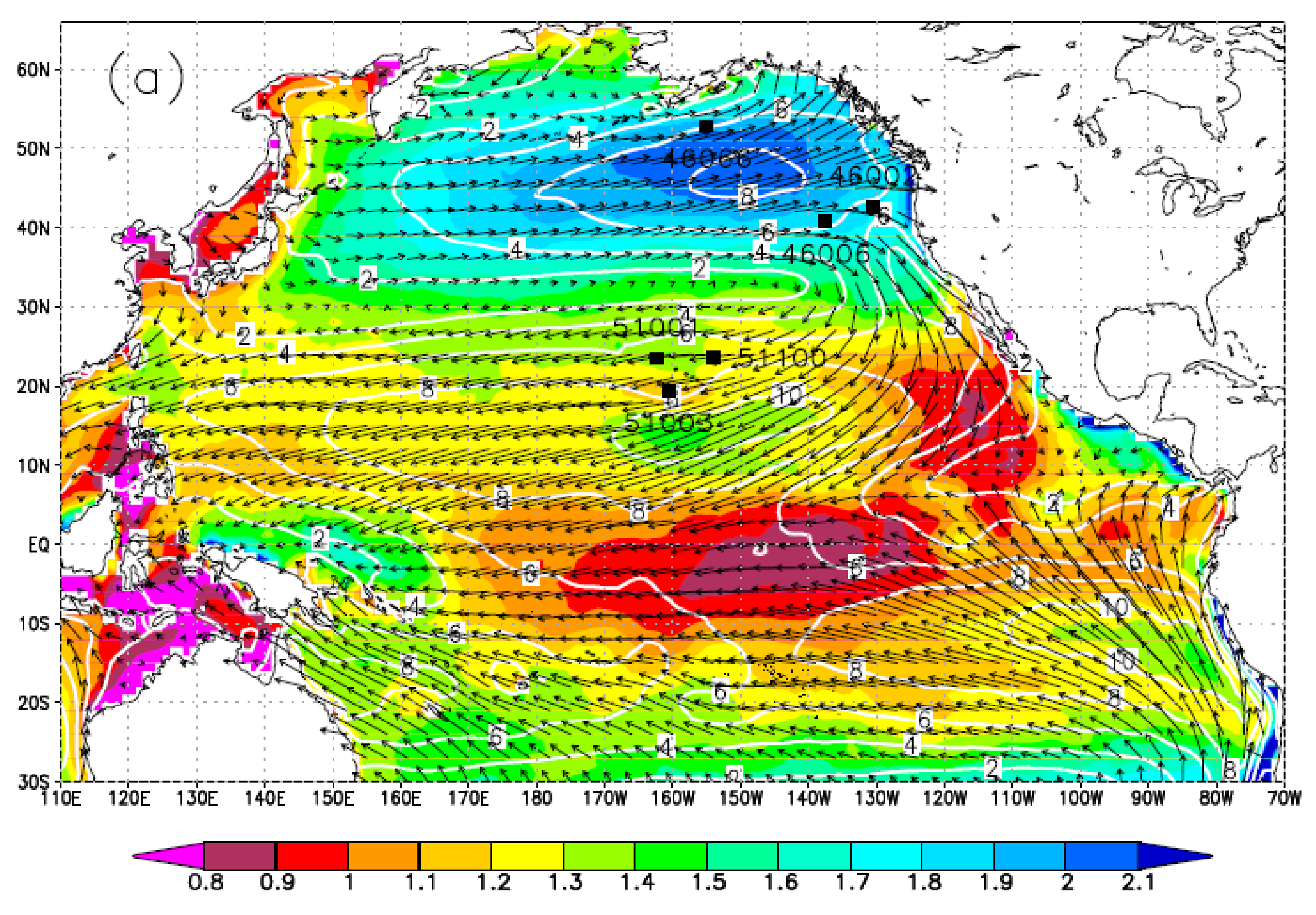
Frequency: 0.04-1.02 Hz (35 grids), Direction: 10º (36 grids)

Wind forcing: NCEP/Reanalysis; 6 hourly
Surface current: Ambe et al (2012)

2006-2010 (5 years)



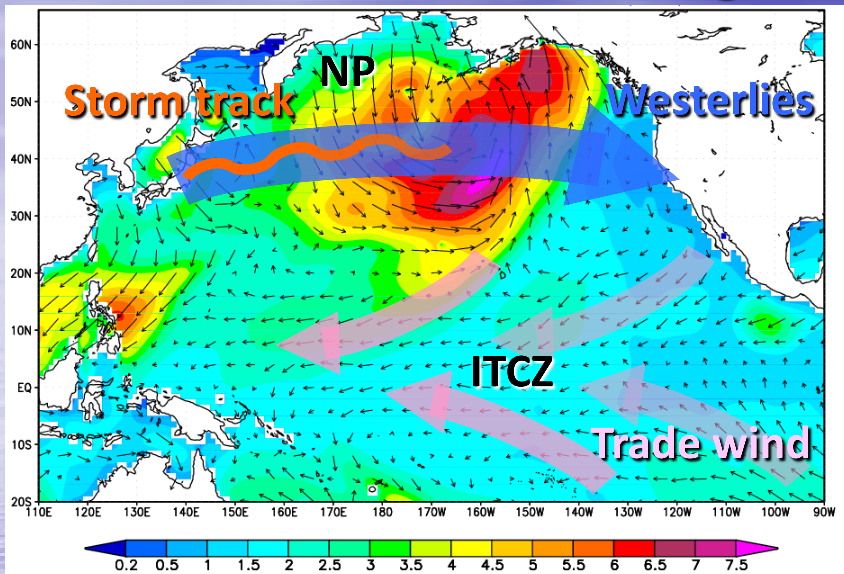
Annual mean of the Stokes drift field (2006-2010)



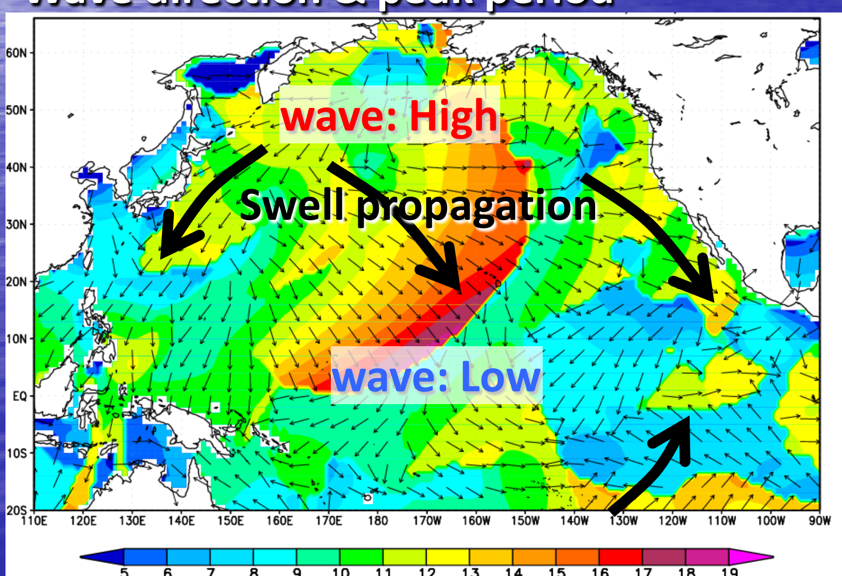
The surface Stokes drift (arrows with white speed contours, cm/s) and Stokes e-folding depths (color, m)

Instantaneous plane view of wind & wave field

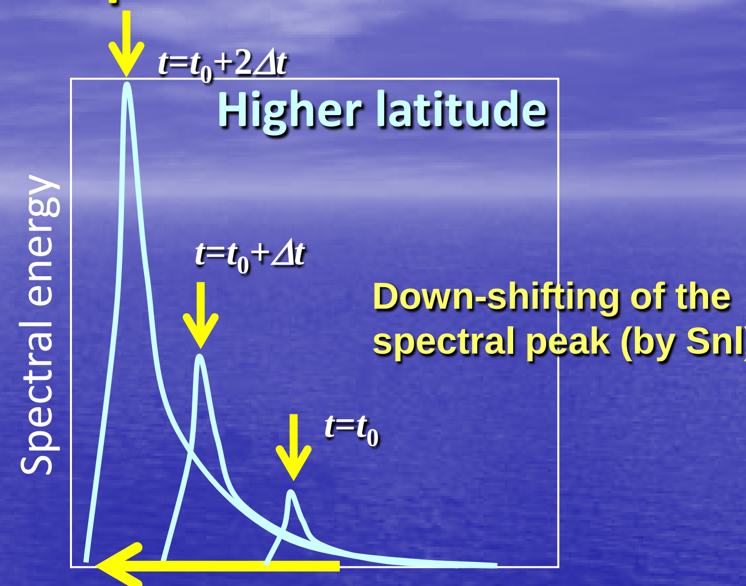
Surface wind vector & wave height

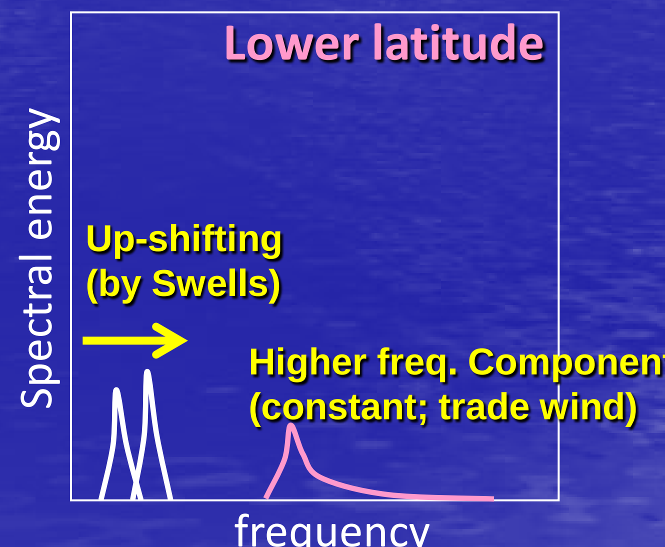


Wave direction & peak period



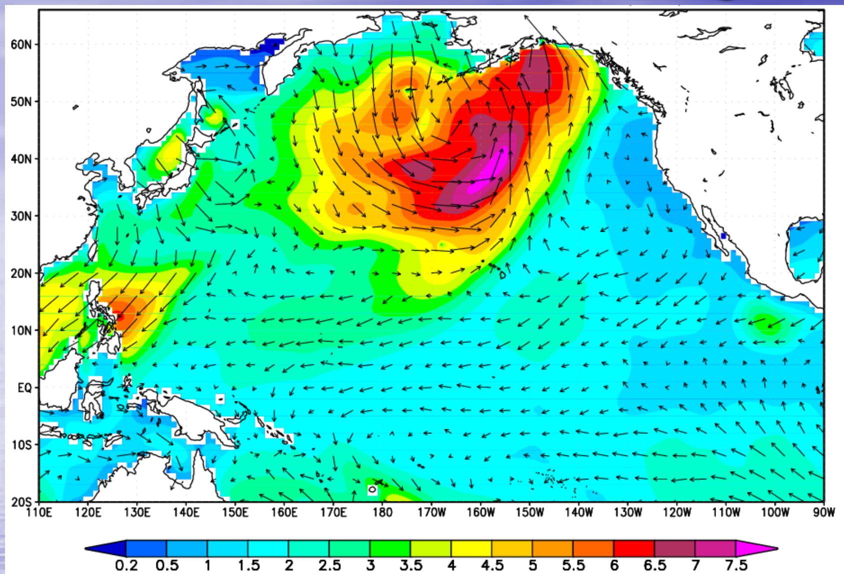
Spectral evolution



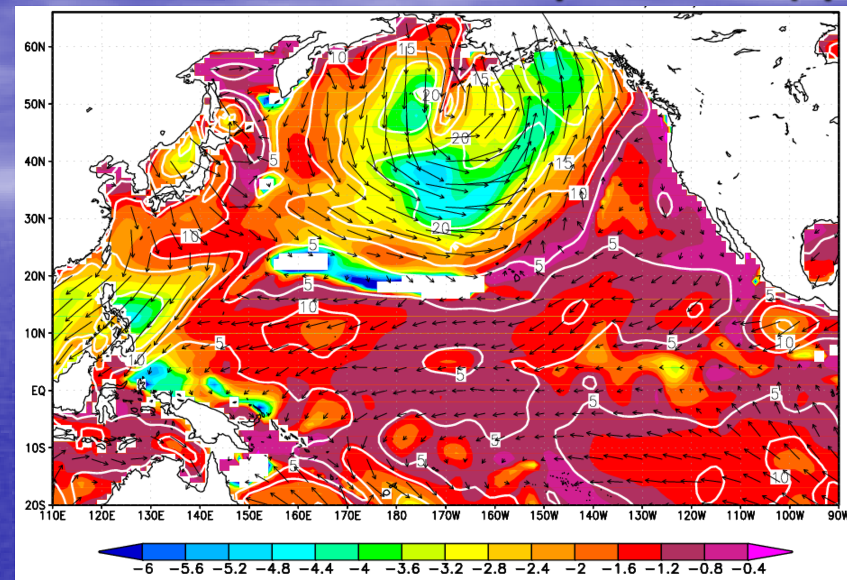


Instantaneous plane view of the Stokes drift

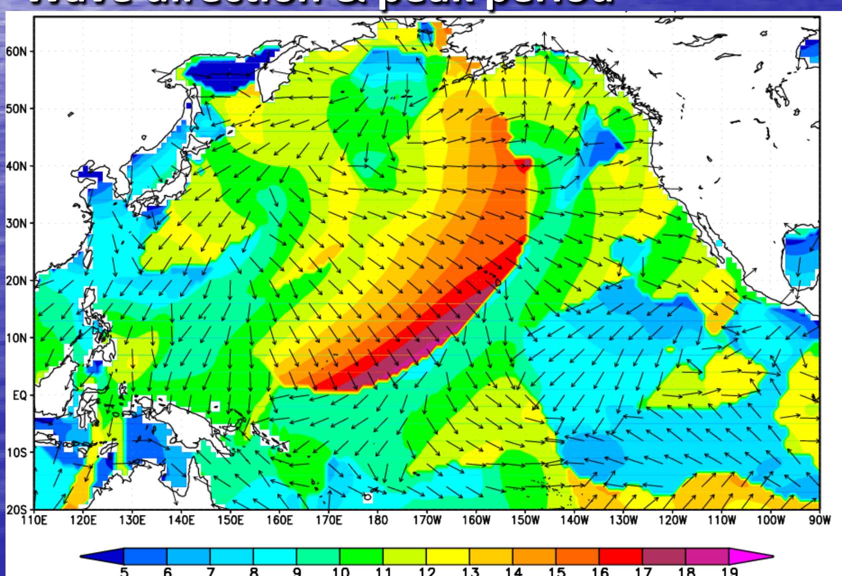
Surface wind vector & wave height



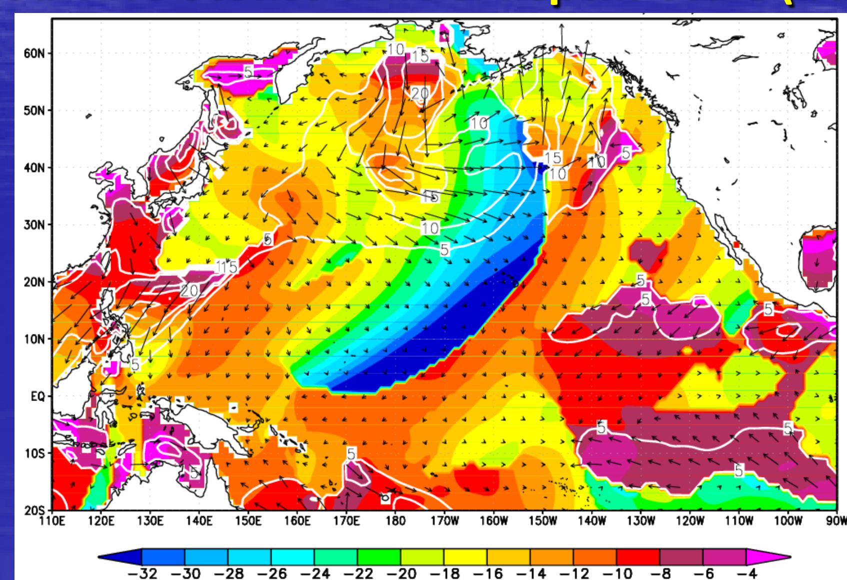
Surface Stokes drift & depths scale (spec)



Wave direction & peak period



Surface Stokes drift & depths scale (bulk)



Validation (surface Stokes drift)

ww3spec: wave spectrum

$$U_S = 2g^{-1}\int \sigma^3 F(\sigma)d\sigma$$

ww3bukl: monochromatic wave

Wave parameters only

$$U_S = g^{-1}\pi^3 H_s^2 T_p^{-3}$$

Ardhuin et al (2009):

Empirical (wind and wave)

$$U_S = f(U_{10}, Hs, fc)$$

Li & Garrett (1993):

Wind speed only

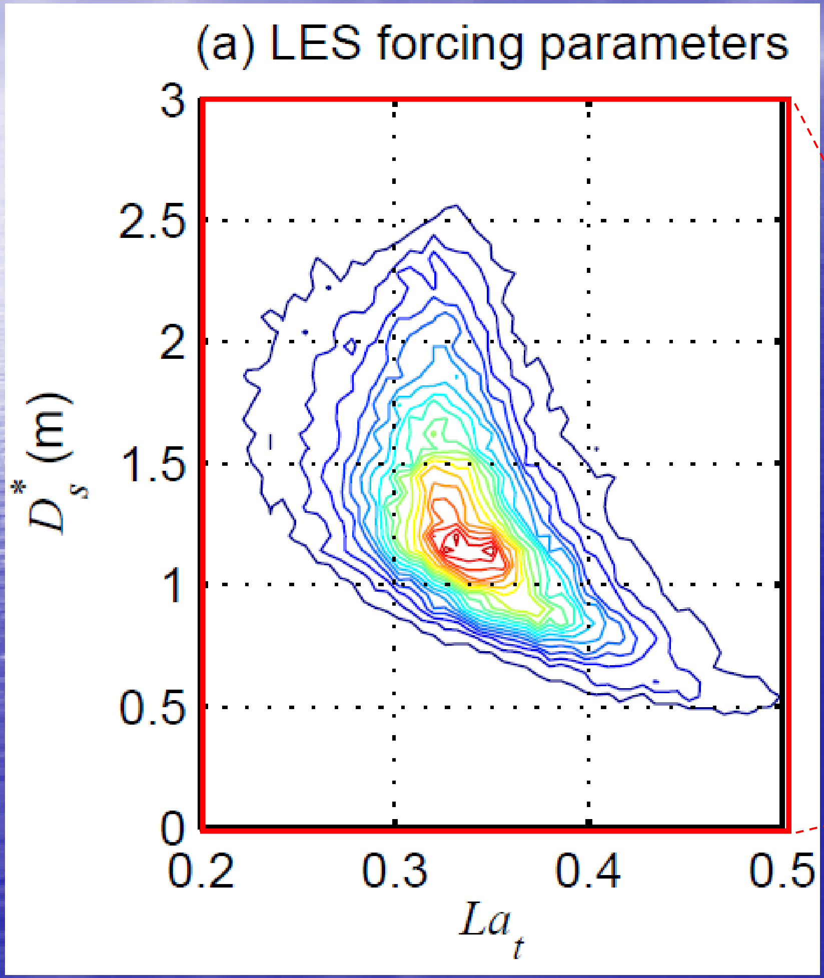
$$U_S = 0.015U_{10}$$

Location		NB (%)	RMSE (cm/s)	C.C.
46002	ww3spec	−2.06	2.84	0.91
N: 25327	ww3bulk	−64.42	9.70	0.71
	AMRFR09	−2.80	3.44	0.86
	LG93	6.83	4.89	0.70
46006	ww3spec	6.45	2.71	0.91
N: 11522	ww3bulk	−63.47	8.92	0.74
	AMRFR09	3.78	3.19	0.87
	LG93	12.70	4.69	0.72
46066	ww3spec	−2.42	3.80	0.89
N: 31447	ww3bulk	−59.20	11.02	0.75
	AMRFR09	−2.61	4.56	0.83
	LG93	2.87	5.97	0.69
51001	ww3spec	9.37	2.04	0.88
N: 32832	ww3bulk	−68.13	6.80	0.62
	AMRFR09	−1.24	2.23	0.82
	LG93	23.04	3.37	0.74
51003	ww3spec	−6.18	2.23	0.78
N: 36684	ww3bulk	−73.29	6.88	0.51
	AMRFR09	−7.51	2.55	0.70
	LG93	19.19	2.95	0.70
51100	ww3spec	21.81	2.19	0.89
N: 14753	ww3bulk	−67.54	5.46	0.59
	AMRFR09	15.92	2.19	0.79
	LG93	46.09	4.04	0.74

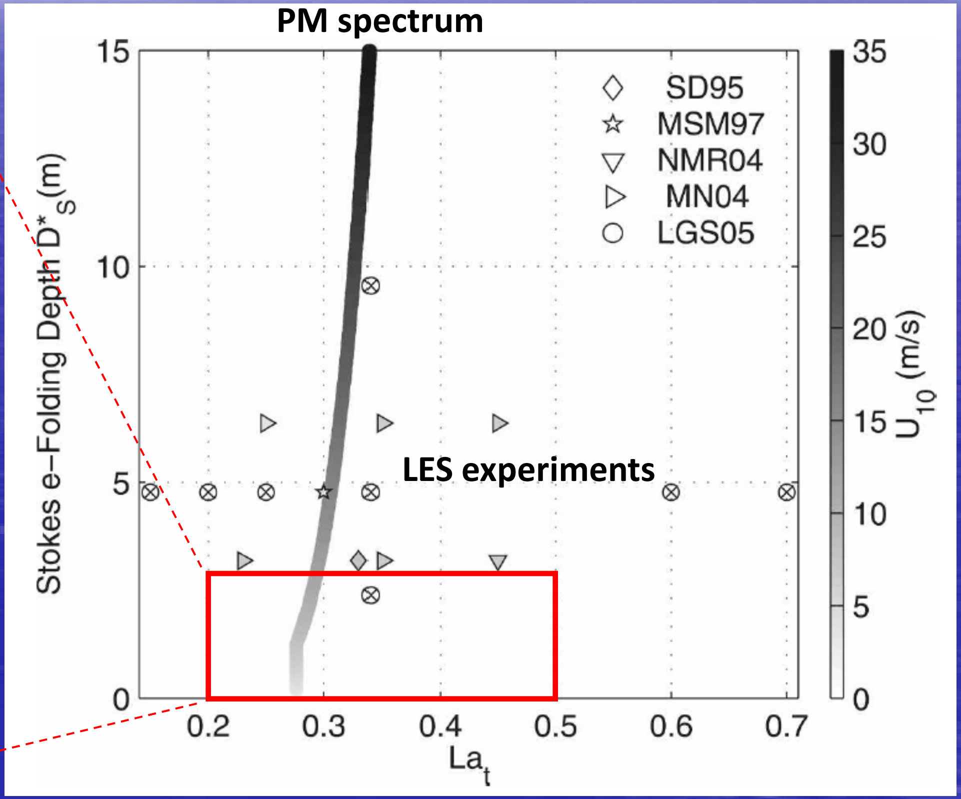
LES forcing parameters for Langmuir Circulation

The turbulent Langmuir number $La_t = \sqrt{u_\tau / U_S}$

& The stokes e-folding depth D_S^*



This study (North Pacific)



Harcourt and D'Asaro (2008)

Wave induced-mass flux

Depth-integrated continuity equation within the Ekman layer

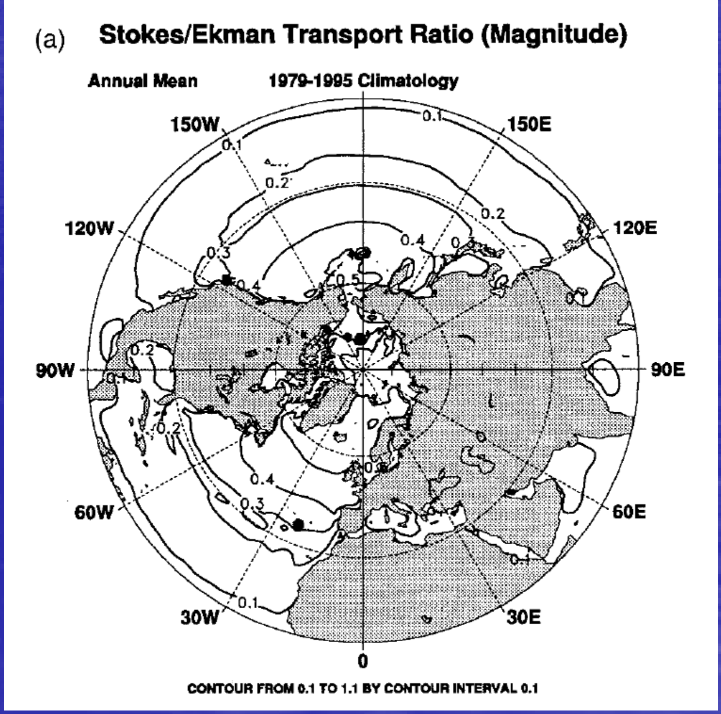
$$\partial_t \bar{\zeta} + \nabla \cdot \boldsymbol{T}_{Ek} = \boxed{-\nabla \cdot \boldsymbol{T}_{St}}$$

Induced by the surface wind, local fetch, and ocean current (wave refraction)

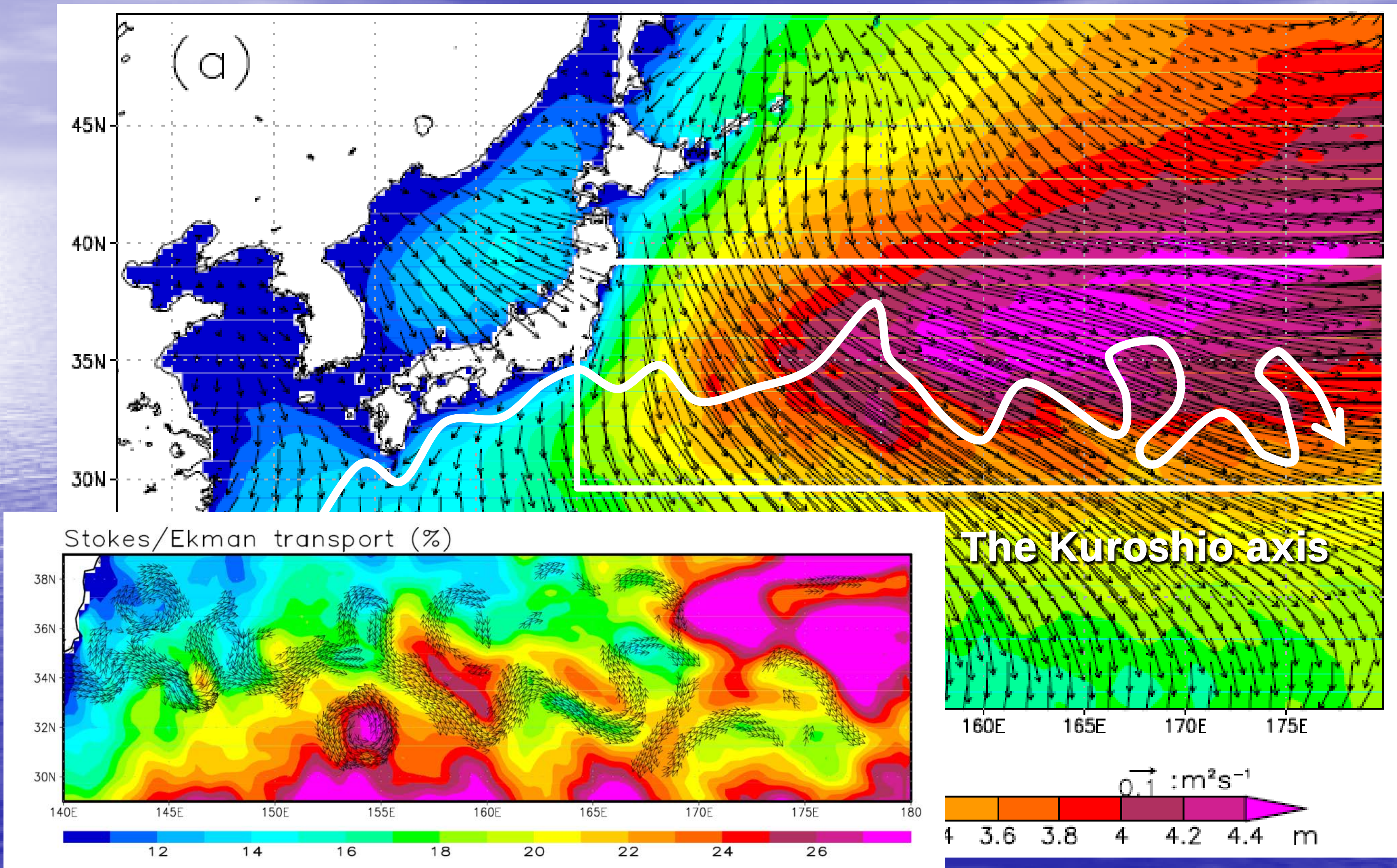
The divergence and convergence of wave induced-mass flux act as sources and sinks of mean flow field at the surface (Hasselmann, 1971)

McWilliams and Restrepo (1999)

estimated from NCEP/reanalysis wind

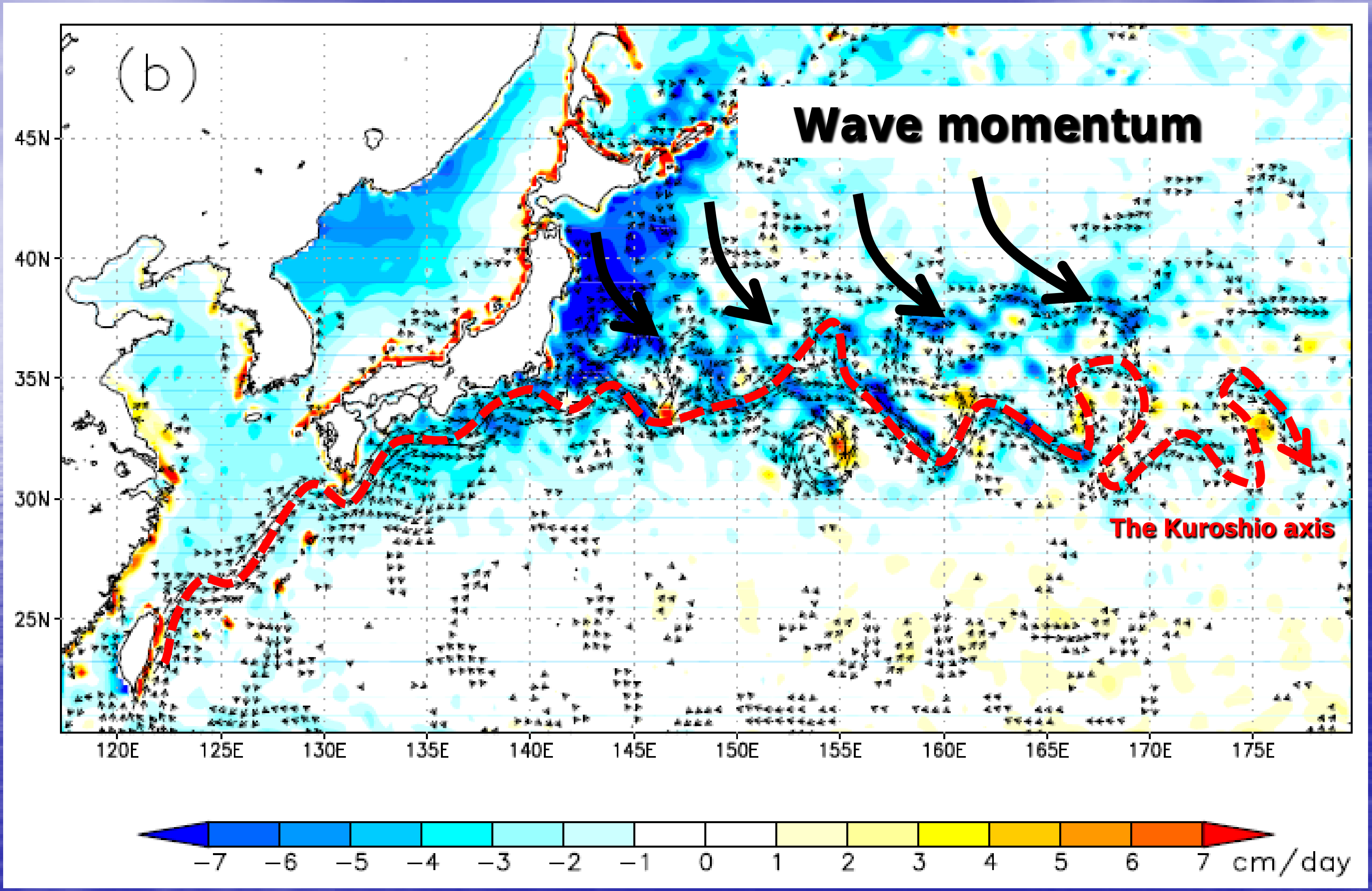


Monthly mean wave field (Feb. 2007)



Significant wave height and wave-induced mass flux

Monthly mean wave field (Feb. 2007)



Divergence of WMF and geostrophic current

Upper ocean mixing: non-wave breaking

□ Kantha and Clayson (2004)

+ Langmuir cells (Stokes production)

$$\frac{\partial q^2}{\partial t}+\ldots=\frac{\partial}{\partial z}\left(K_q\frac{\partial q^2}{\partial z}\right)+2K_M\left[\frac{\partial u}{\partial z}\left(\frac{\partial u}{\partial z}+\frac{\partial u_{stokes}}{\partial z}\right)+\frac{\partial v}{\partial z}\left(\frac{\partial v}{\partial z}+\frac{\partial v_{stokes}}{\partial z}\right)\right]+\ldots$$

□ Qiao et al. (2004)

wave-turbulence correlation $Bv\ (E,k;z)$

$$\overline{uw}=\overline{(\bar{u}+\tilde{u}+u')(\bar{w}+\tilde{w}+w')}$$

$$=\overline{\bar{u}\bar{w}}+\overline{\tilde{u}\tilde{w}}+\boxed{\overline{\tilde{u}w'}+\overline{u'\tilde{w}}}+\overline{u'w'}$$

Radiation stress

Reynolds stress

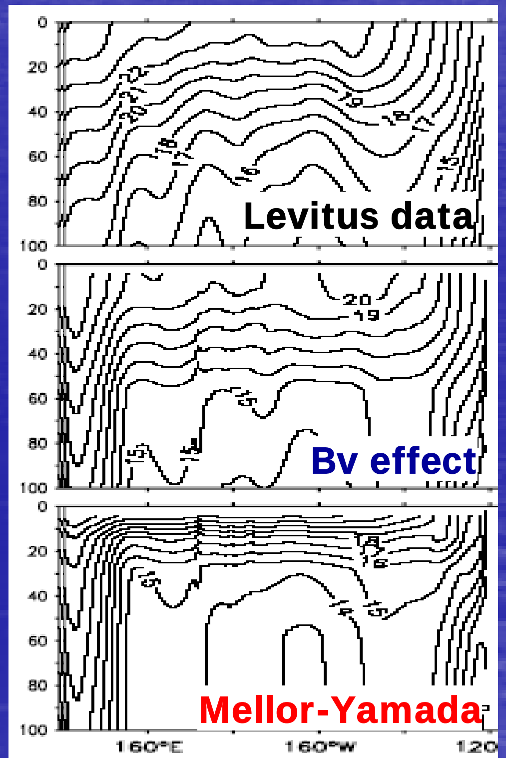
$$-\overline{\tilde{u}w'}=-\overline{\tilde{w}u'}=Bv\frac{\partial\bar{u}}{\partial z}$$

$$\frac{DT}{Dt}=\frac{\partial}{\partial z}\left\{\left(K_H+Bv\right)\frac{\partial T}{\partial z}\right\}$$

$$Bv\sim u_s\exp(3kz)$$ (Qiao et al. 2010)

monthly mean temp.

depth



1D experiments

Experiment conditions

Water depth: 500 m (dz=1m), 30°N

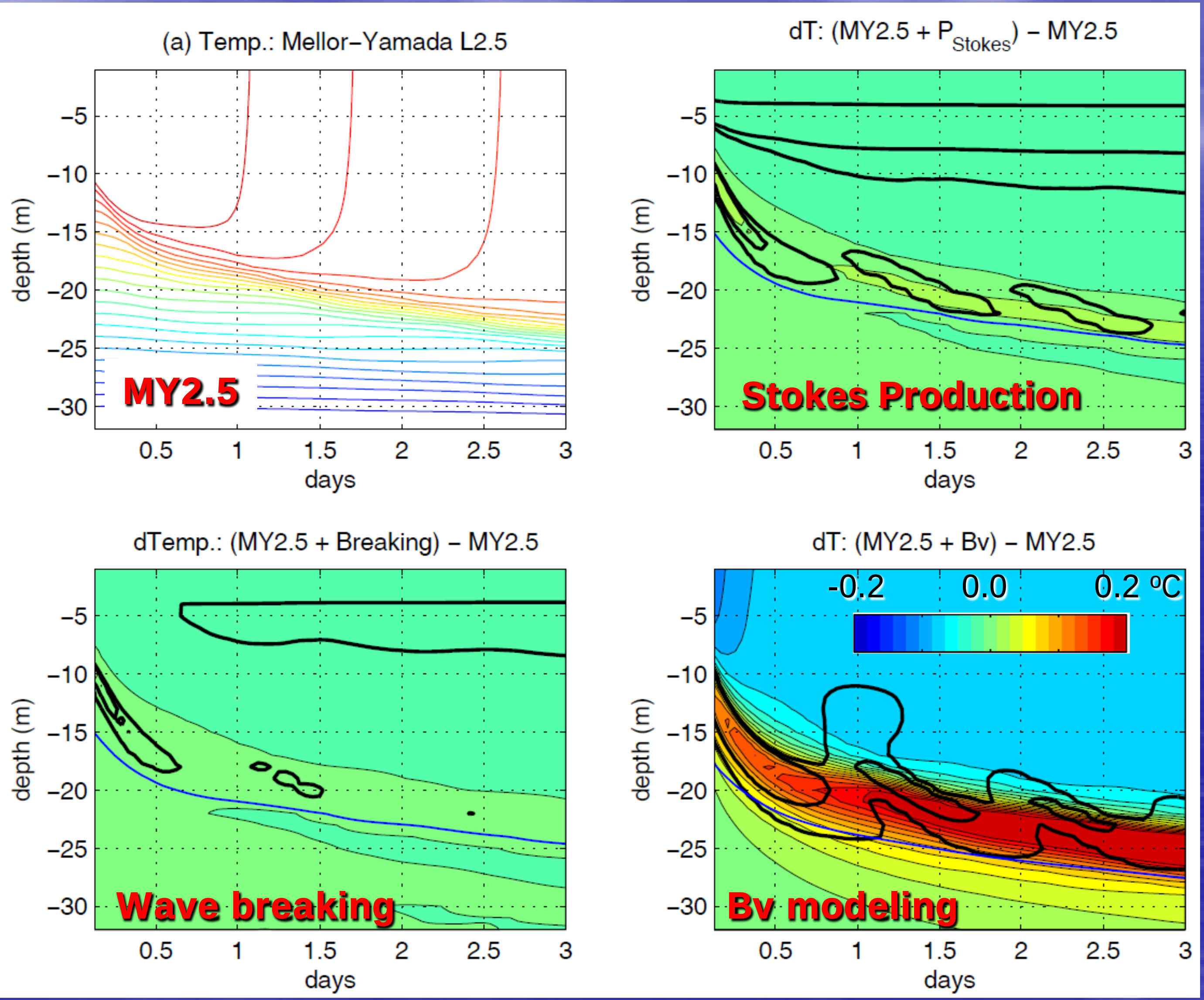
Temperature stratification: $T_0(z) = \max(24 + 0.05z, 5)$

wind speed: 8.5m, wave filed Hs: 1.65, Tp: 5.9s

Without the Stokes-Coriolis force in momentum equations

MY2.5: Mellor and Yamada L2.5 closure model
MB04 : Mellor and Blumberg (2004); Wave breaking
KC04: Kantha and Clayson (2004); Stokes production
Q04 : Qiao et al. (2004); Bv modeling

Temporal evolution of temperature and vertical viscosity



Conclusions

We investigated the Stokes drift in realistic wave fields and its impact on vertical mixing in the upper ocean by using a third generation wave model.

Stokes drift strongly depends on spectral shape.

In the Pacific Ocean, mean Stokes e-folding depth scale is of the order of the significant wave height.

The spatial characteristics of the Stokes drift can be explained by considering the spectral evolution of ocean surface waves.

The divergence of wave induced-mass flux is significantly modified by local fetch, the coast and ocean currents.

For the application of wave-current coupling processes to OGCM, it is clear that high vertical resolution is required to accurately represent the Stokes drift field.