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Connection Between Time Scales: Turbulence, Waves, Weather, Climate

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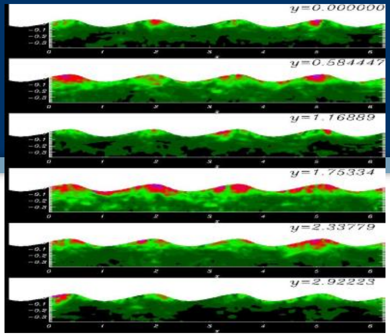


wave mixing in the upper ocean

- wave-induced turbulence (not to be confused with wave-breaking turbulence) is produced at the vertical scale of wavelength
- important for sediment suspension, tropical cyclones, weather, climate, polar oceans and ice
- laboratory experiments, numerical simulations, field observations – all give similar rates for wave turbulence production

Waves and ocean turbulence

- in air-sea interaction and ocean-mixing models, the wind stress is usually parameterised to directly drive the dynamics of the upper ocean
- wind provides momentum and energy fluxes to the ocean surface and thus mixes the upper ocean
- dominant part of the wind stress, however, is supported by the flux of momentum from wind to waves
- these waves break, and the breaking is regarded as the main source of the turbulence across the interface
- it is often assumed that the turbulence is then diffused down and the mixing is achieved
- if the wave breaking was the only role of the waves in the upper-ocean mixing, such a scheme would perhaps be feasible
- there are, however, two potential problems in such approach

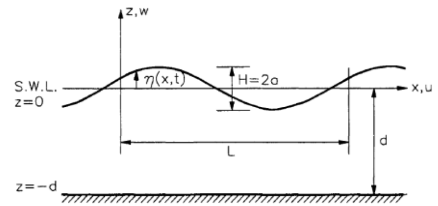
Waves and ocean turbulence

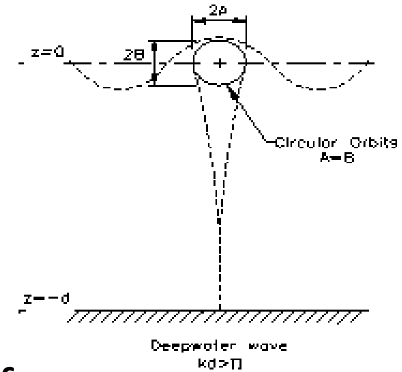
- there are, however, two potential problems in such approach
- first of all, time scales of the turbulence lifetime and turbulence diffusion down to some 100m should agree
- secondly, before the momentum is received by the upper ocean in the form of turbulence and mean currents, it goes through a stage of surface wave motion
- such motion can directly affect or influence the upper-ocean mixing and other processes, and thus ignoring the wave phase of momentum transformation may undermine accuracy and perhaps even validity of such parameterisations
- there are at least two processes in the upper ocean which can deliver turbulence straight to the depth of 100m or so instead of diffusing it from the top
- these are wave-induced turbulence and Langmuir circulation
- 2-3m of the ocean water have the same heat capacity as the entire atmosphere

Hypothesis of the Wave Reynolds Number

$$\eta(x,t) = a_0 \cos(\omega t + kx)$$

$$a(z) = a_0 \exp(-kz)$$





It is the hypothesis that the a-based Reynolds number

$$\mathrm{Re} = \frac{aV}{\nu} = \frac{a^2\omega}{\nu}$$

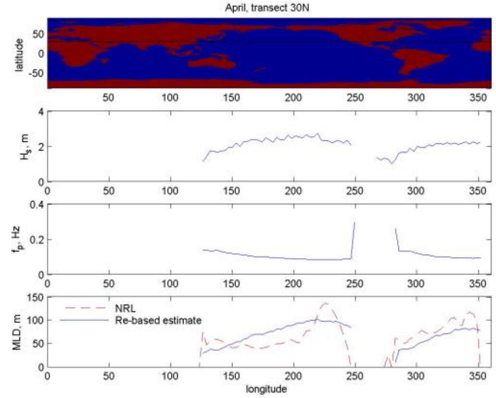
where *V=ωa* is orbital velocity, and *ν* is kinematic viscosity of the ocean water, indicates transition from laminar orbital motion to turbulent

Critical Reynolds Number for the Wave-Induced Motion, and Depth of the Mixed Layer

Re_{cr}=3000

$$\mathrm{Re}(z) = \frac{\omega}{\nu} a_0^2 \exp(-2kz) = \frac{\omega}{\nu} a_0^2 \exp(-2\frac{\omega^2}{g} z)$$

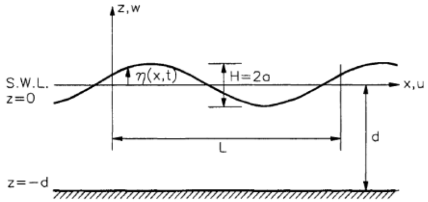
$$z_{cr} = -\frac{1}{2k} \ln(\frac{\mathrm{Re}_{cr}\,\nu}{a_0^2 \omega}) = \frac{g}{2\omega^2} \ln(\frac{a_0^2\omega}{\mathrm{Re}_{cr}\,\nu})$$



Babanin, GRL, 2006

Linear Wave Theory. Governing equations

- Most fluid mechanics problems can be solved by considering the governing Equations of conservation of mass, momentum and energy



Young, 1999, Elsevier

Define the velocity potential φ

$$u = -\frac{\partial \varphi}{\partial x}, \quad w = -\frac{\partial \varphi}{\partial z}$$

- Laplace Equation (Continuity Equation) - conservation of mass (two-dimensional case):

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0$$

- Unsteady Bernoulli Equation – conservation of momentum:

$$\frac{p}{\rho} + gz - \frac{\partial \varphi}{\partial t} = 0$$

$$\varphi(x,z,t) = \frac{ag}{\omega} \frac{\cosh[k(d+z)]}{\cosh[kd]} \cos(kx - \omega t)$$

Kinsman, 1965: Wind Waves based on Phillips (1961)

Solutions

Navier-Stokes equation

linearised boundary conditions, with surface tension *T*

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\nabla^2 u$$

$$\frac{\partial w}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\nabla^2 w - g$$

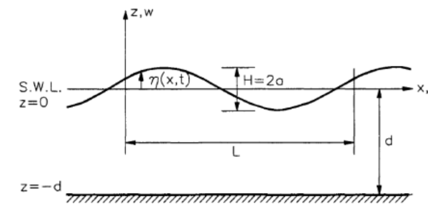
$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial \eta}{\partial t} = w_{z=0}$$

$$p - 2\mu\frac{\partial w}{\partial z} = -\frac{\partial^2 \eta}{\partial x^2}\mathrm{T}_{z=\eta}$$

$$\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} = 0_{z=\eta}$$

vorticity



$$\omega = \frac{\partial w}{\partial x} - \frac{\partial u}{\partial z} = \nabla^2\Psi$$

$$\omega = \beta\frac{i\sigma}{\nu}e^{mz}e^{i(kx+\sigma t)} =$$

$$= -2\gamma k\sigma\exp\left(\sqrt{\frac{\sigma_{real}}{2\nu}}z - \frac{2\sigma_{real}}{\mathrm{Re}_w}\right)\exp\left\{i\left(kx + \sqrt{\frac{\sigma_{real}}{2\nu}}z + \sigma_{real}t\right)\right\}$$

$$\frac{\delta_z}{\lambda} = \frac{1}{\lambda}\sqrt{\frac{2\nu}{\sigma_{real}}} = \frac{1}{2\pi}\sqrt{\frac{2\nu k^2}{\sigma_{real}}} = \frac{\sqrt{2}}{2\pi}\frac{1}{\sqrt{\mathrm{Re}_w}}$$

- exponential decay in *z* and *t*
- oscillations in *x*, *z* and *t*
- ‘length’ of vertical vorticity oscillation is much smaller than *λ*

Dai et al., JPO, 2010

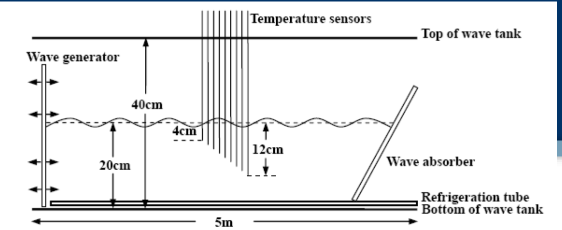


Figure 1. Sketch of the laboratory setup.

Mixing the stratified fluid
experiment (left), model (right)

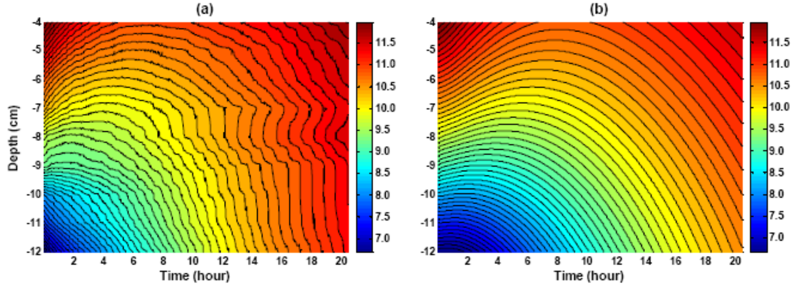
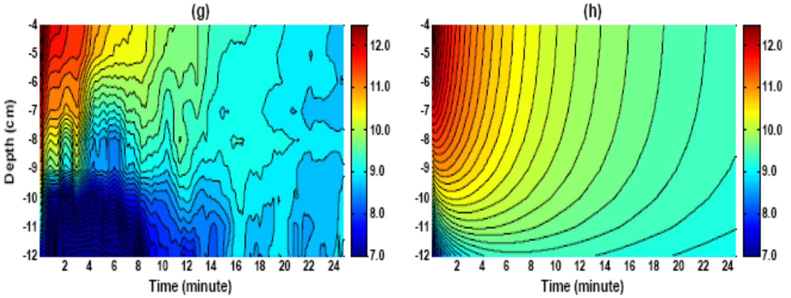


Figure 2. Evolution of the water-temperature profile without waves. (a) observations; (b) numerical simulation with the one-dimensional model. The time is in hours.



no waves
time scale: hours

non-breaking waves
time scale: minutes

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Regardless of the turbulence source, 3D turbulence is unstable to 2D wave orbital motion

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C00J30, doi:10.1029/2012JC007948, 2012

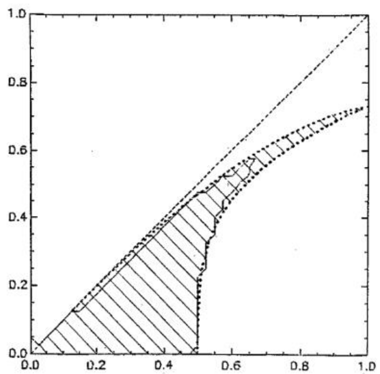


Figure 1. Diagram of stability of solutions of equation set (22) on the (ε_1, ε_2) plane. Here ε_1 is the horizontal axis and ε_2 is the vertical axis. F1 corresponds to $\varepsilon_2 = \varepsilon_1$; $F2_1$ corresponds to $\varepsilon_2 = \varepsilon_1 - 0.3\,\varepsilon_1^3 + 0.03\,\varepsilon_1^4$, $0 \le \varepsilon_1 \le 1$; $F2_2$ corresponds to $\varepsilon_2 = 0.9(\varepsilon_1 - 1/2)^{0.3}$, $1/2 \le \varepsilon_1 \le 1$; and F3, the dashed curve, corresponds to the numerical calculations using the Floquet theory [*Hale*, 1969].

On the turbulence generated by the potential surface waves

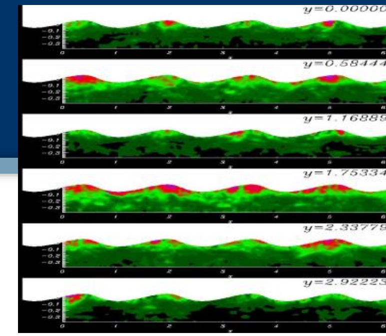
A. Y. Benilov[1]

Received 31 January 2012; revised 8 May 2012; accepted 12 June 2012; published 18 August 2012.

[1] The turbulence (the random vortex motions) of the upper ocean is nourished by the energy and momentum of the surface waves (the potential motion). The statistical characteristics of the turbulence (turbulent kinetic energy, dissipation rate, and Reynolds stresses) depend on the state of the ocean surface waves. This paper discusses the possibilities of generating this turbulence using the vortex instability of the potential surface waves. The vortex component of fluctuations of velocity field and possibly the interaction between both the vortex and potential motions cause the vertical transport of the momentum. The Reynolds tensor is a linear function of the correlation tensor of vortex field. The initial small vortex perturbations always exist in the upper ocean because of the molecular viscosity influences, especially near the free surface, and the fluctuations of the seawater density. The horizontal inhomogeneities of the seawater density produce the vortex field even if the initial vorticity was zero and the initial flow was the potential flow. The evolution of the small initial vortex disturbances in the velocity field of potential linear surface waves is reduced to a coupled set of linear ordinary differential equations of the first order with periodic coefficients. The solution of this problem shows that the small initial vortex perturbations of potential linear surface waves always grow. The initial small vortex perturbations interacting with the potential surface wave produce the small-scale turbulence (Novikov's turbulence) that finally causes the viscous dissipation of the potential surface wave. The wave-induced turbulence can be considered as developed turbulence with a well distinguishable range of the turbulent wave numbers k where turbulence obeys the Kolmogorov's self-similarity law.

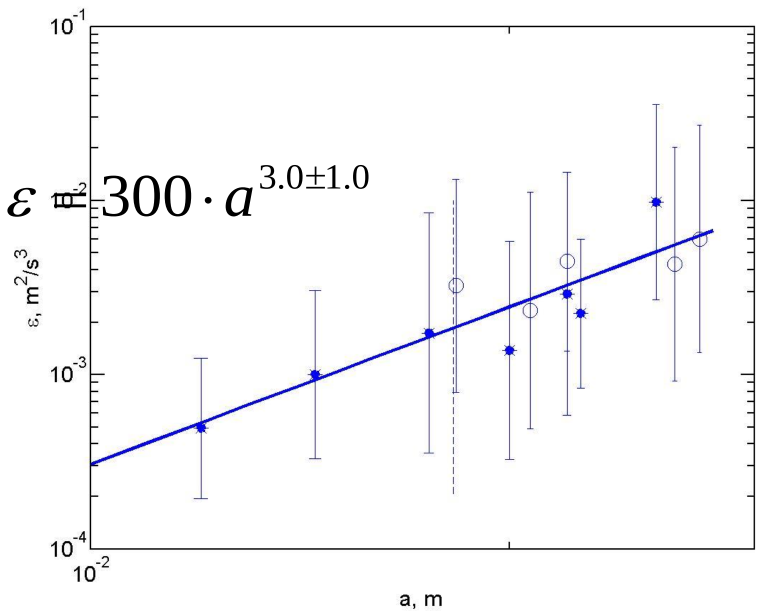
Citation: Benilov, A. Y. (2012), On the turbulence generated by the potential surface waves, *J. Geophys. Res.*, *117*, C00J30, doi:10.1029/2012JC007948.

Benilov, JGR, 2012

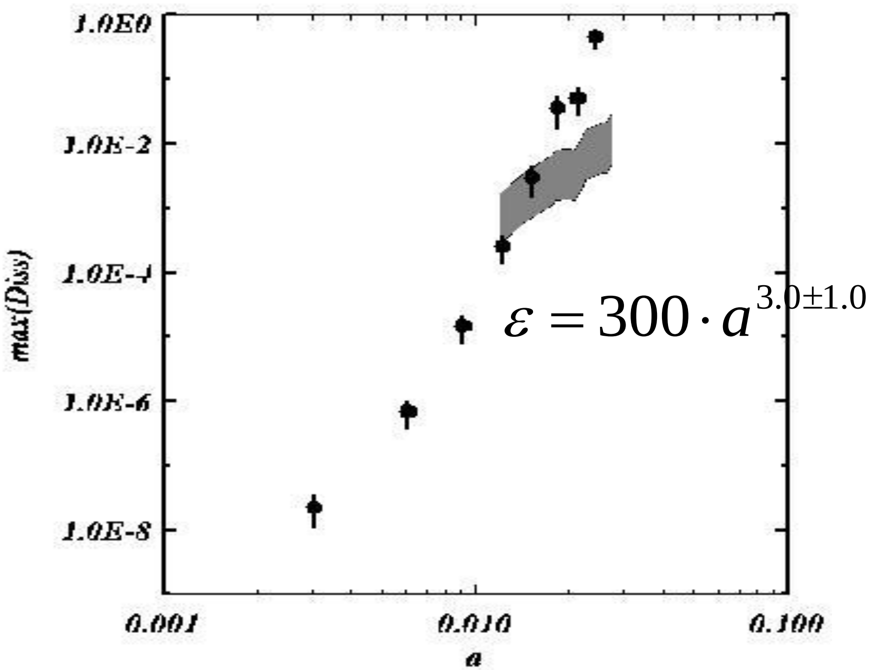


Model of generation of turbulence by nonlinear waves

Model is based on exact 2-D (x-z) model of surface waves coupled with 3-D LES (x-y-z) model of vortical motion based on Reynolds equation with parameterised subgrid turbulence



Lab experiment,



Babanin & Haus, JPO, 2009

Babanin & Chalikov, JGR, 2012

Swell attenuation

$$\varepsilon = 300 \cdot a^{3.0\pm1.0} \quad b = b_1 k\omega^3 = 30. \quad b_1=0.004$$

Dissipation

$$\epsilon_{dis} = b_1 k\omega^3 a_0^3 = 0.004 k u_{orb}^3.$$

- volumetric

$$D_a = b_1 k \int_0^\infty u(z)^3 dz = b_1 k u_0 \int_0^\infty \exp(-3kz) dz = \frac{b_1}{3} u_0^3.$$

- per unit of surface

$$D_x = \frac{1}{c_g} D_a = \frac{b_1}{3} 2 \frac{k}{\omega} u_0^3 = \frac{2}{3} b_1 k \omega^2 a_0^3 = \frac{2}{3} b_1 g k^2 a_0^3.$$

- per unit of propagation distance

$$\frac{g}{2} \frac{\partial (a_0(x)^2)}{\partial x} = \frac{2}{3} b_1 g k^2 a_0(x)^3,$$

$$a_0(x)^2 = \frac{4}{B^2} x^{-2} = \frac{9}{4 \cdot b_1^2 k^4} x^{-2} = \frac{9}{64} 10^6 k^{-4} x^{-2}.$$

Babanin, 2011, CUP

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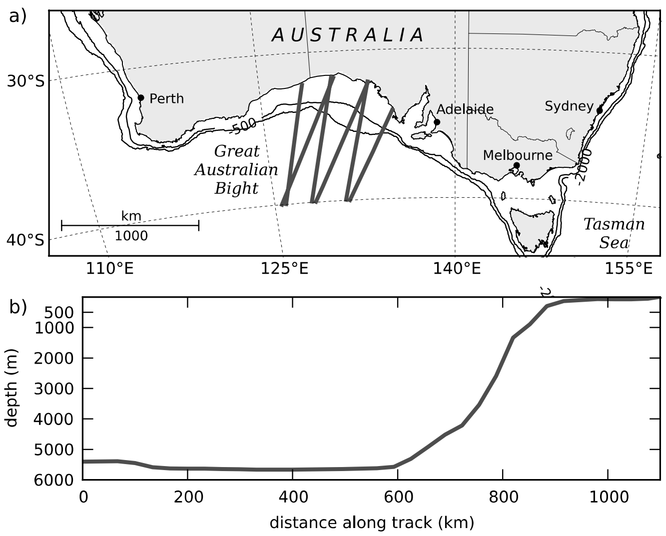
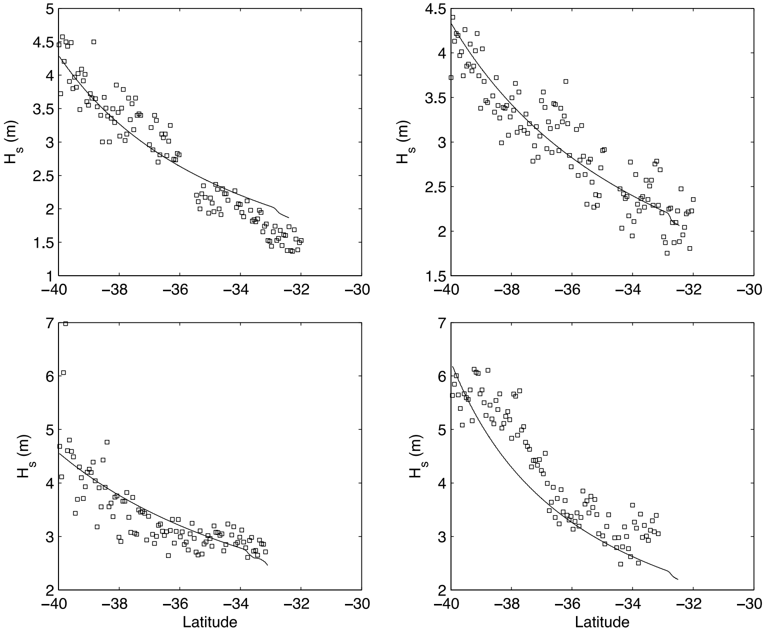
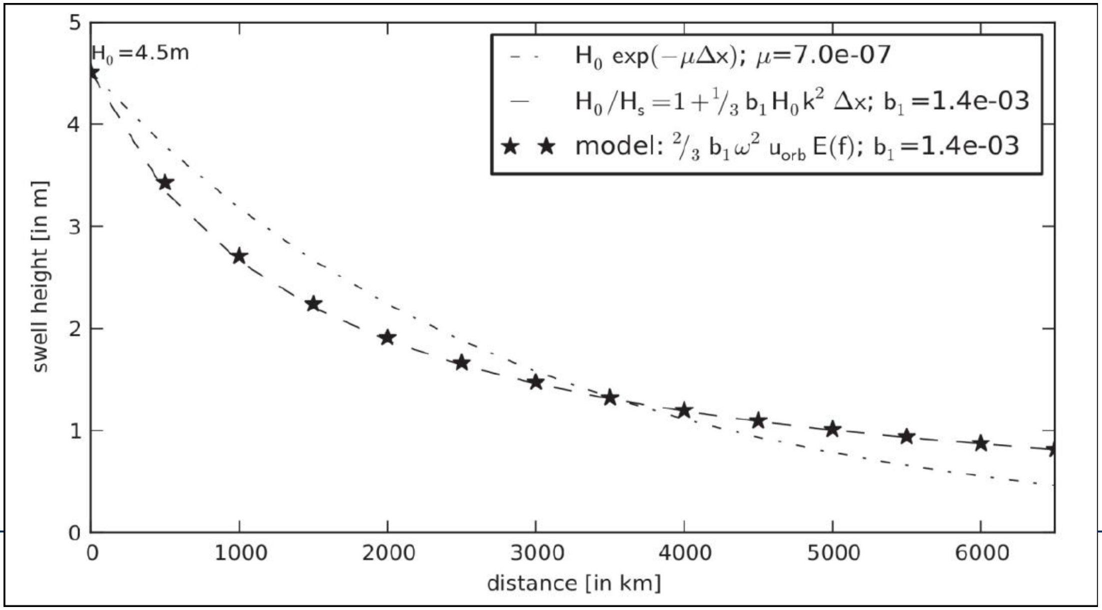
Swell attenuation

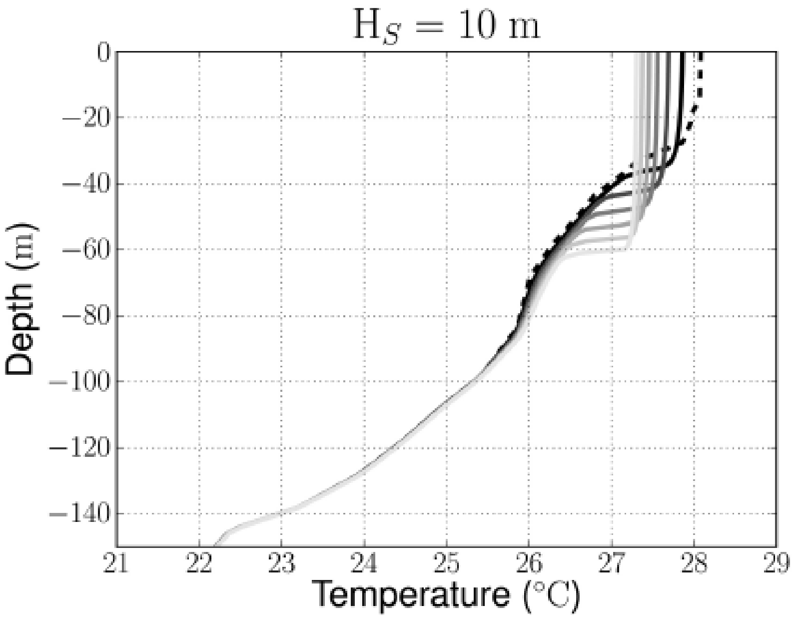


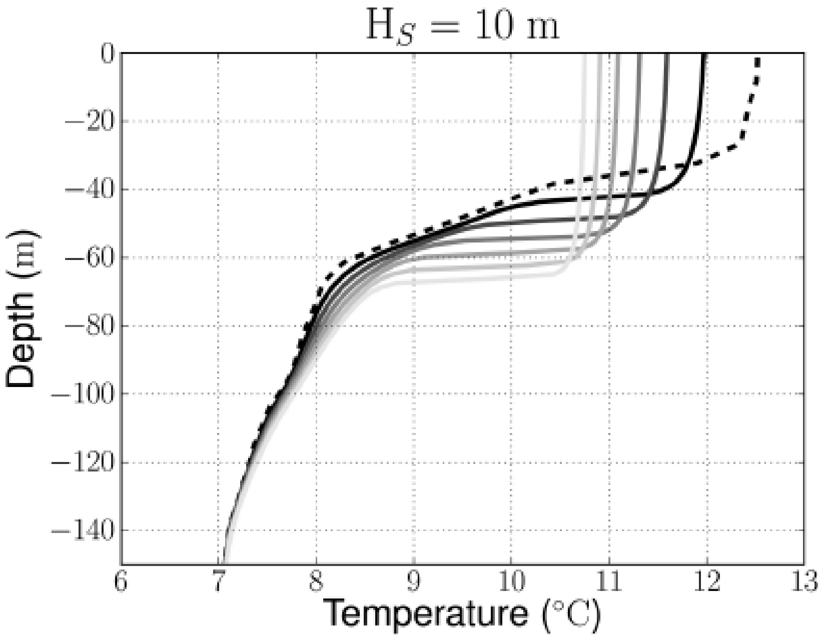




Young, Babanin, Zieger, JPO, 2013

Modelling SST and MLD at the scale of tropical cyclone





Ghantous and Babanin, Nonlin. Proc. in Geophysics, 2014

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1002/2016MS000878

Key Points:
- Mixing from unbroken surface waves under tropical cyclones can modify ocean surface temperatures by up to 0.5°C

Simulated ocean response to tropical cyclones: The effect of a novel parameterization of mixing from unbroken surface waves

Lachlan Stoney[1], Kevin Walsh[2], Alexander V. Babanin[1], Malek Ghantous[3], Pallavi Govekar[4], and Ian Young[1]

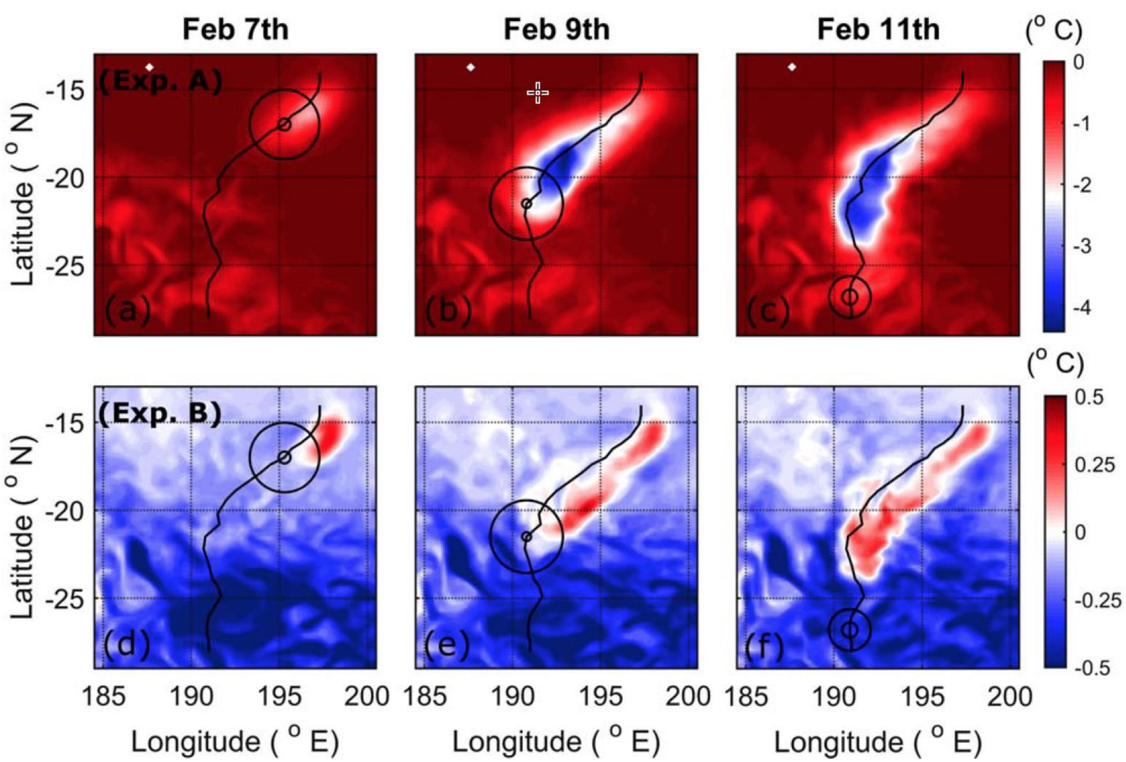


Figure 3. The development of the cold wake from Tropical Cyclone Dovi, 2003. The top plots (a–c) show the potential temperatures at 5 m depth from Experiment A, while the bottom plots (d–f) show the wave-induced anomalies thereof from Experiment B. Values are daily averages. The storm moved along the black line from top right to bottom left, with the inner and outer circles representing the *RMW* and R34, respectively, for each day at 12:00 UTC. Note the different color scales.

- Southern Hemisphere TC
- MOM5
- (top) no waves
- (bottom) warm anomalies on the side with the strongest winds and cool anomalies in other regions
- initial wave-induced deepening of the mixed layer, which can modify the subsequent shear-induced entrainment and upwelling
- could potentially influence tropical cyclone intensity and structure

Journal of Advances in Modeling Earth Systems

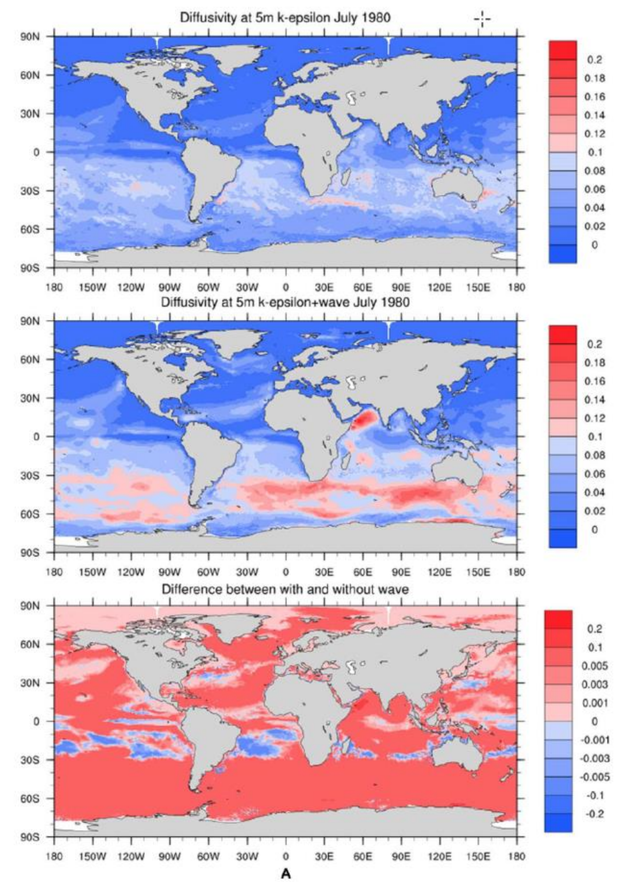
RESEARCH ARTICLE
10.1002/2016MS000707

The effect on simulated ocean climate of a parameterization of unbroken wave-induced mixing incorporated into the k-epsilon mixing scheme

Kevin Walsh[1], Pallavi Govekar[1,2], Alexander V. Babanin[3], Malek Ghantous[4], Paul Spence[5,6], and Enrico Scoccimarro[7,8]

Key Points:

- The inclusion of a process that is missing from most climate models causes noticeable changes in Southern Ocean regional ocean



- MOM5 global modelling
- Diffusivity at 5m
- Without (top) and with (middle) waves; difference (bottom)
- Left: 1980
- Right: 2007

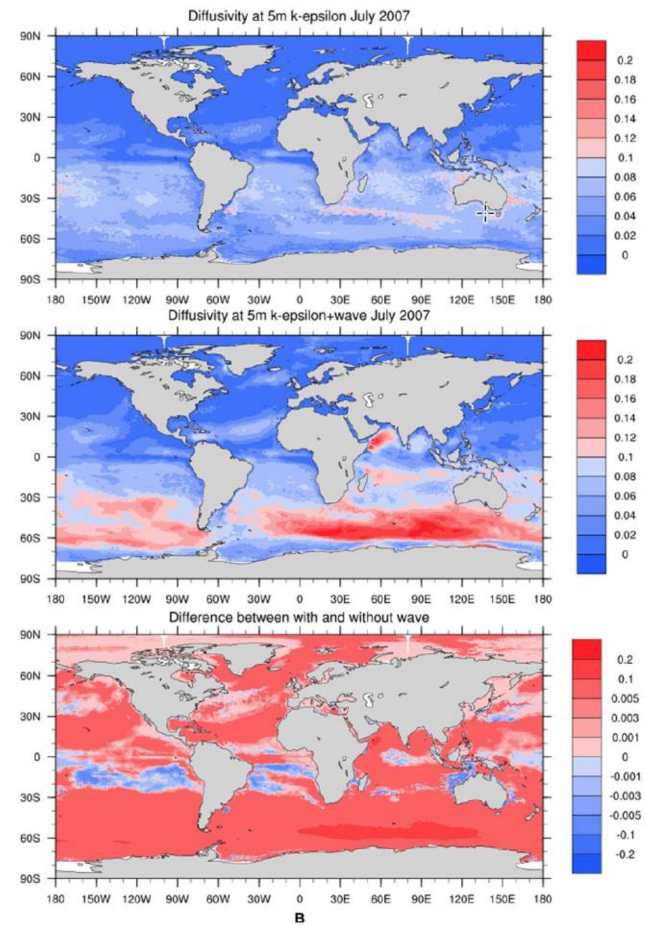


Figure 4. (a) Diffusivity ($m^2 s^{-1}$) at 5 m depth, for July 1980, without (top plot) and with (middle plot) the wave-mixing parameterization, and the difference, mixing included minus without (bottom plot). (b) The same as Figure 4a for 2007.

Figure 4. (continued)

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1002/2016MS000707

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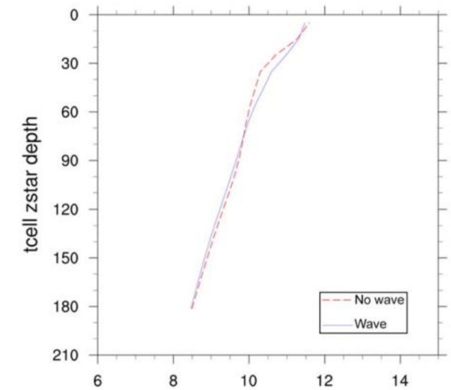


Figure 14. Comparison of global average ocean temperature profiles (°C) for July 1980, wave-mixing included (solid line) versus no wave (dashed line). Vertical axis is in meters and refers to the temperature levels in the model.

Table 1. Biases Versus the World Ocean Atlas (2009) Data (http://data.nodc.noaa.gov/woa/WOA09/) for the Two Simulated Years, Without and With Wave-Mixing Included, at Specified Ocean Depths for Selected Latitude Bands[a]

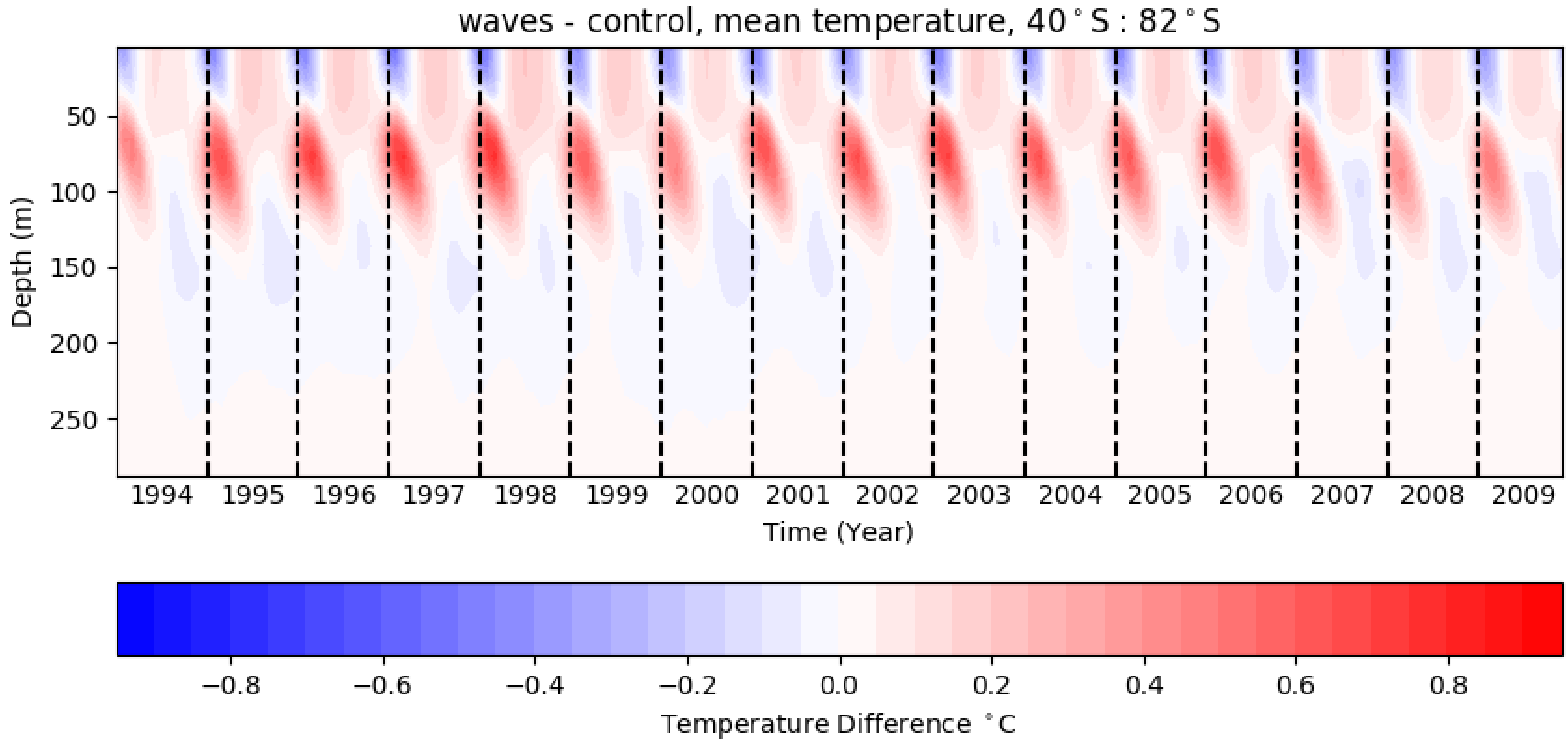
	1980				2007			
	December Without	December With	July Without	July With	December Without	December With	July Without	July With
5 m Temperature								
Global	0.11	0.03	0.17	0.05	0.31	0.22	0.18	0.07
70°S–50°S	−0.11	−0.25	−0.18	−0.06	0.26	0.05	−0.43	−0.25
50°S–30°S	0.61	0.20	0.08	0.14	0.38	0.00	−0.21	−0.16
30°S–30°N	0.18	0.17	0.29	0.22	0.55	0.54	0.52	0.45
30°N–50°N	−0.15	0.18	1.02	−0.15	−0.46	−0.17	1.45	0.29
50°N–70°N	−0.56	−0.22	0.99	−0.19	−0.74	−0.35	0.78	−0.37
25 m Temperature								
Global	0.06	0.08	−0.05	0.09	0.27	0.29	−0.01	−0.11
70°S–50°S	−0.15	−0.18	−0.16	−0.04	−0.03	0.01	−0.41	−0.48
50°S–30°S	0.27	0.15	0.14	0.20	0.22	0.03	−0.15	−0.42
30°S–30°N	0.20	0.24	0.13	0.21	0.65	0.68	0.46	0.27
30°N–50°N	−0.08	0.25	−0.65	−0.20	−0.40	−0.11	−1.23	−0.30
50°N–70°N	−0.49	−0.16	−0.73	0.01	−0.67	−0.29	−0.71	−0.33
55 m Temperature								
Global	−0.02	0.17	−0.02	0.12	0.18	0.39	0.07	0.19
70°S–50°S	−0.22	−0.04	−0.14	−0.04	−0.39	−0.09	−0.29	−0.21
50°S–30°S	−0.43	−0.06	0.20	0.26	−0.31	0.01	−0.10	−0.05
30°S–30°N	0.31	0.42	0.11	0.23	0.77	0.89	0.51	0.60
30°N–50°N	−0.02	0.39	−0.48	0.15	−0.26	0.07	−0.92	−0.39
50°N–70°N	−0.27	0.07	−0.71	−0.17	−0.45	−0.07	−0.81	−0.14

[a]Regions where the introduction of wave-induced mixing reduces the bias are shaded.

MOM5 global modelling

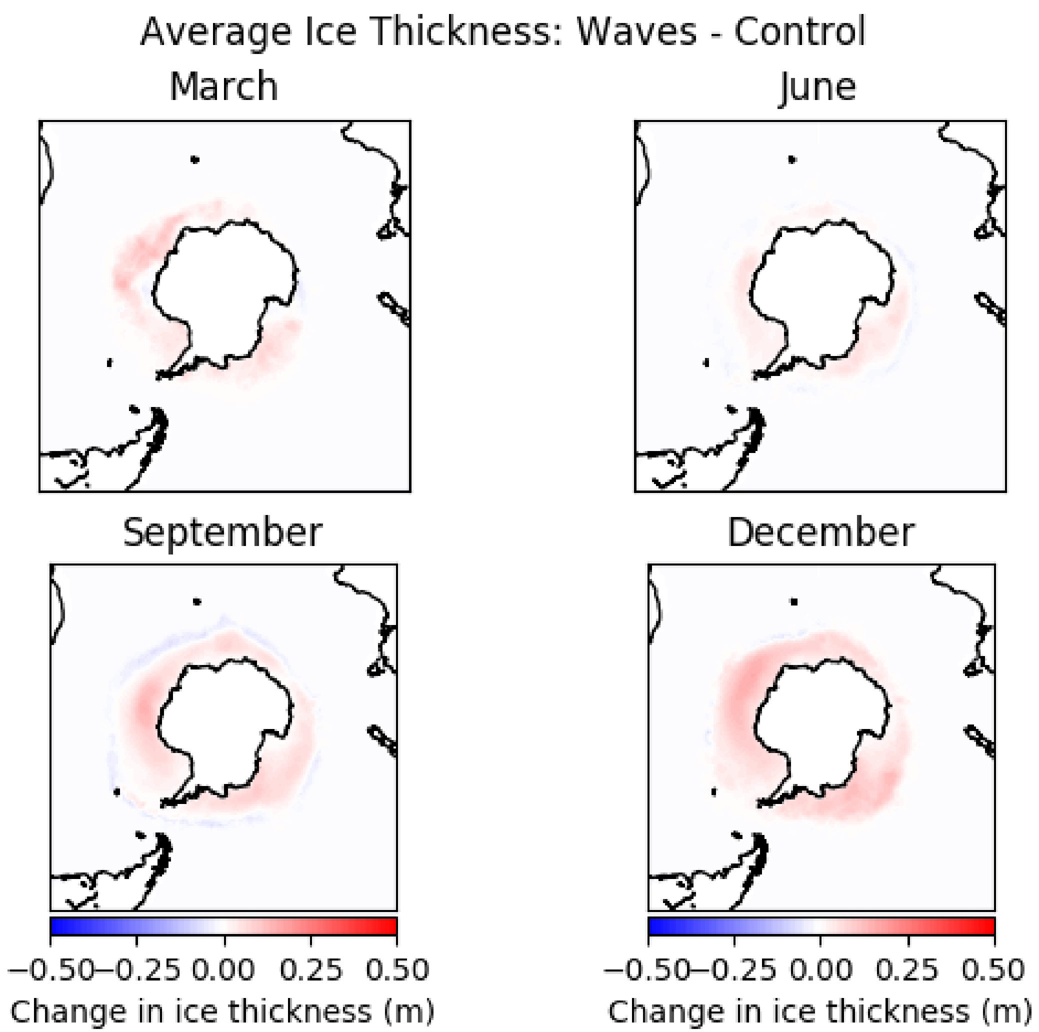
Results from MOM5 Ocean model with and without the inclusion of an extra wave mixing term (from WW3)

Temperature difference between ocean models with and without the extra wave-mixing term (wave and control, respectively).



In the Southern Ocean an increase in wave mixing captures more heat and transports it into deeper waters over the (southern) summer. While producing a net increase in ocean temperature this results in the waters surface being colder during the summer.

Thomas et al., 2019, OD



Difference in ice thickness between ocean models with and without the extra wave-mixing term (wave and control, respectively).

The decrease in surface temperature despite the net increase in ocean heat content causes a reduction in the amount of ice melt during the summer. This results in a thicker Antarctic sea sheet, particularly in December (summer).

Conclusions

- coupling of small-scale models (waves, turbulence) with large-scale models (weather, climate) is necessary
  - physics is continuous
  - computing capabilities allow the coupling
- waves provide feedback
  - to the atmospheric boundary layer
  - to the upper ocean (usually overlooked)
  - to the large-scale air-sea interactions
- wave climate also changes

Pleskachevsky et al., *JPO*, 2011

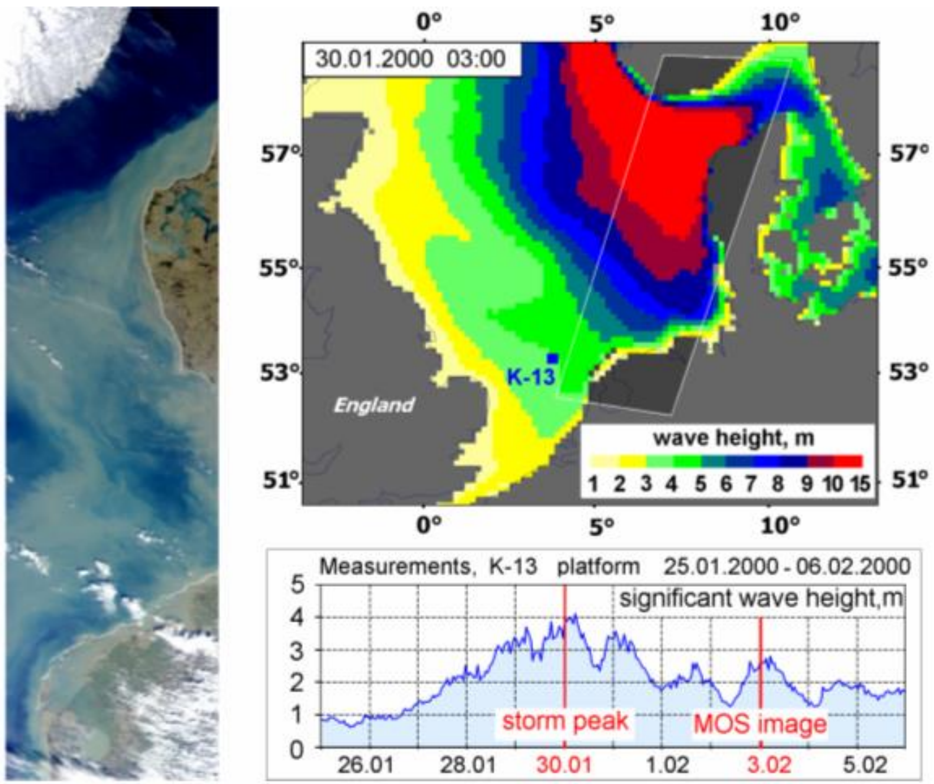
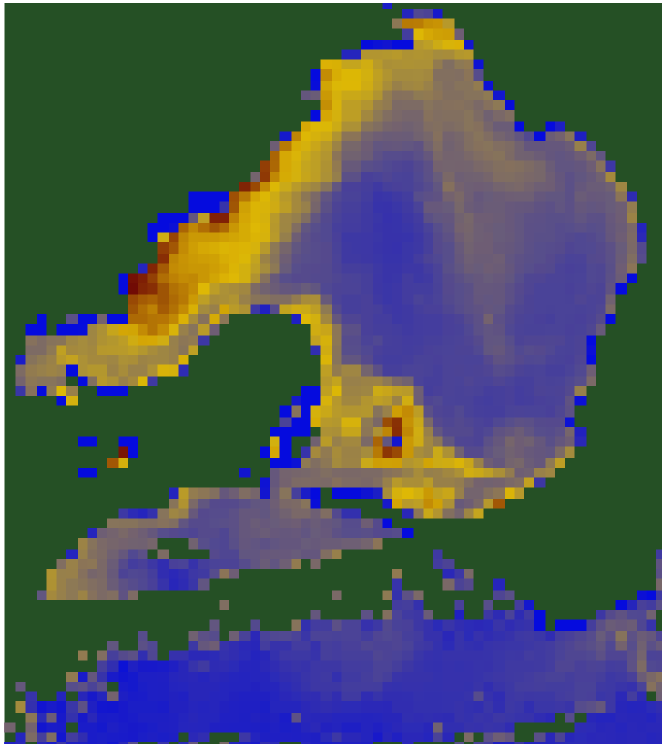


FIG. 1. Storm events in the North Sea at 29.01-04.02.2000 (the storm peak on 30.01.2000, at about 03:00 UTC). Optical MOS image of German Bight on 03.02.2000 (left) and significant wave height in the North Sea at the storm peak (right).



field observations and modelling, North Sea (left), Port Phillip (right)

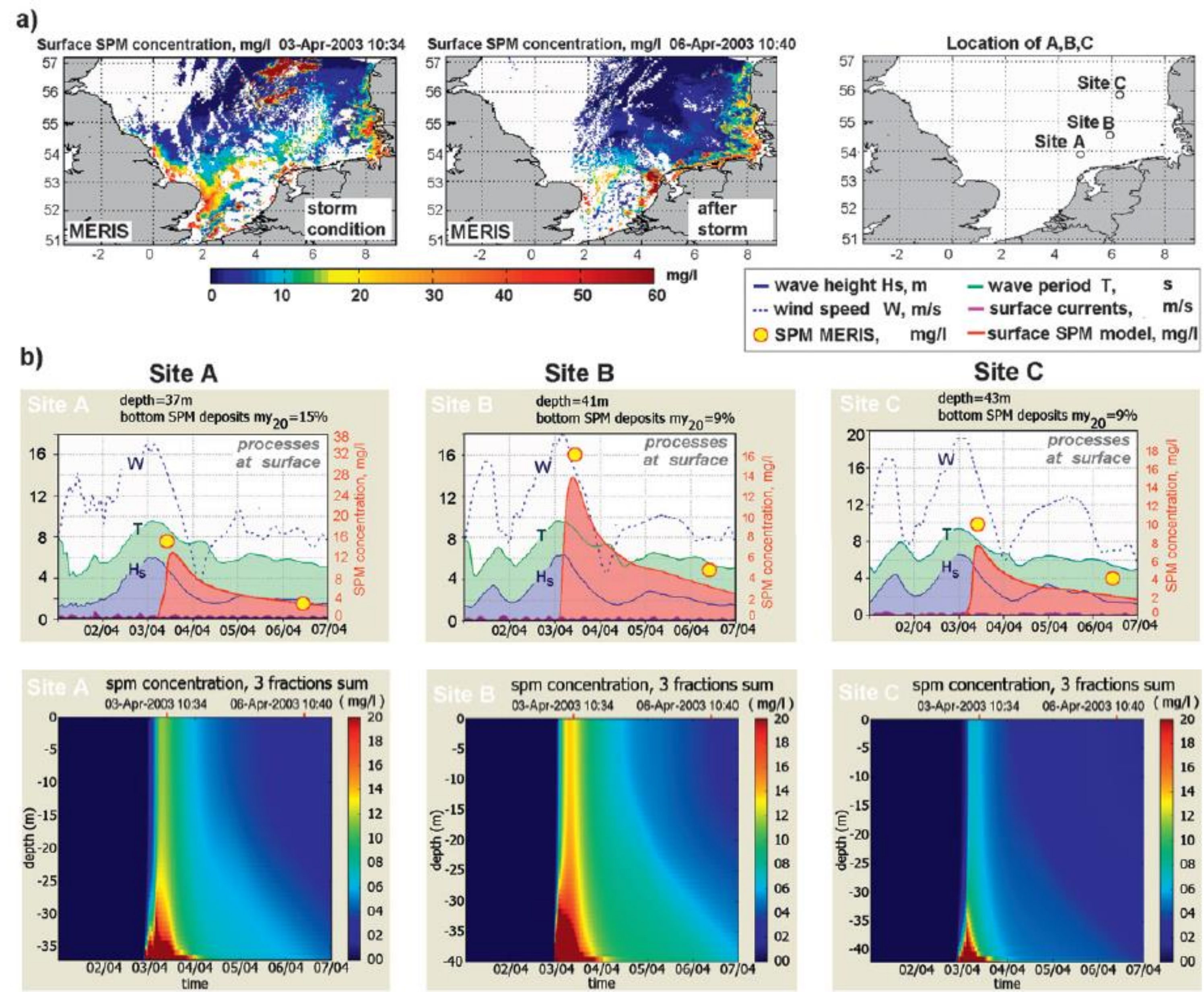


FIG. 7. The storm period 1–7 Apr 2003 in the southern North Sea. (a) MERIS scenes, presenting the SPM concentration at sea surface and locations of sites A, B, and C. The plume-shaped structure is visible during the storm but then disappears after the wave height sinks.