Impacts of sea surface temperature gradients and surface roughness changes on the motion of surface oil: A simple idealized study

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Outline

• Why do it?
• How to do it?
  (1) Method: The Univ. of Washington Planetary Boundary Layer (UWPBL) model embedded with a revised surface roughness scheme
  (2) Experimental setup
• What do we get?
  Key Results: Changes in atmospheric PBL features with different SST gradients, particularly in the transition zones:
  1) Changes in Surface winds, surface wind divergence;
  2) Ekman transport and its dependence on SST gradients;
• Summary
Why do it: Because of some shortcomings in most oil trajectory forecast models:

• Treat oil as a passive tracer (virtual particles);
• Underestimate influence of SST gradient on near-surface winds on small spatial scales;
• Physical processes owing to surface roughness discrepancy between seawater and oil may not be fully considered
Hypothesis of potential feedback

- Surface Oil (Water)
- SST gradient
- Surface waves
- Surface wind divergence/convergence
- Oceanic Ekman transport
- Surface wind stress
- Surface winds

PBL theory
Inputs: SSTs, Tair, humidity, geostrophic winds

Outputs: Wind profile, wind stress, etc.

Roughness length parameterization for water (Bourassa 2006)

Roughness length parameterization for oil (Bourassa 2006)

• Aerodynamically smooth surface
• Capillary waves damped by surface oil
• Gravity waves damped by surface oil
3-D schematic diagram for experimental setup

Model resolution and input variables:
• Model domain: 90W-87W, 27N-30N
• Oil domain: 89W-88W, 28N-29N
• Resolution: $\delta X$ by $\delta Y = 0.04^\circ X 0.04^\circ$
• $U_{geo}$ is about 8 m/s
• Air humidity = 0.02 kg/kg
• SST = 25°C for water;
  $= 25^\circ C + \delta T$ for oil
• $T_{air} = 24.5^\circ C$ for water;
  $= 24.5^\circ C + \delta T$ for oil
• $\delta T = 0.001, 0.002, ..., 0.04^\circ C$
• Temperature gradient = $\delta T/\delta X$ in unit of °C per 0.04°.

Note: Assumption of SST gradient between oil and seawater is supported by satellite observations (Svejkovsky et al. 2012)
What do we get?

• Surface winds
• Surface wind divergence/convergence
• Oceanic Ekman transport
surface wind speed

(a) SST\_grad = 0 °C/0.04°

(b) SST\_grad = 0.01 °C/0.04°

(c) SST\_grad = 0.02 °C/0.04°

(d) SST\_grad = 0.04 °C/0.04°

Temperature difference

Roughness shift

(u,v) \rightarrow 15 \text{ m/s}
Surface wind divergence ($x \times 10^5 \text{ s}^{-1}$)

(a) SST$_\text{grad} = 0 \degree \text{C}/0.04\degree$

(b) SST$_\text{grad} = 0.01 \degree \text{C}/0.04\degree$

(c) SST$_\text{grad} = 0.02 \degree \text{C}/0.04\degree$

(d) SST$_\text{grad} = 0.04 \degree \text{C}/0.04\degree$

Atmospheric 2$^{\text{nd}}$ circulation

Downward motion

Upward motion

SST gradients affect surface wind divergence in the boundary
SST gradients affect Ekman transport in the boundary.

Relative zonal Ekman transport (kg/ms)

(a) SST_grad = 0.02 °C/0.04°

(b) SST_grad = 0.04 °C/0.04°

Relative meridonal Ekman transport (kg/ms)

(c) SST_grad = 0.02 °C/0.04°

(d) SST_grad = 0.04 °C/0.04°

(mx,my) → 100kg/ms
• Net convergence of Oceanic Ekman transport → downwelling

• Surface wind divergence(convergence) in the boundary → atmospheric secondary circulation
Summary

• There are significant changes in surface winds, wind speed, wind divergence, and oceanic Ekman transport in the transition zones between water and oil, which in turn may play a role in influencing the surface oil motion. Both the strong SST gradient and roughness change in the transition zones play an important role in these changes;

• An atmospheric secondary circulation can be induced as a consequence of strong wind divergence in the transition zones, which in turn affects the surface oil motion.

• A net convergence of oceanic Ekman transport tends to push the oil downward to the subsurface. The orientation of oceanic Ekman transport owing to air surface temperature gradient and roughness change tends to spin the surface oil and deform the surface oil.
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Changes in magnitude and directions of wind stress and Ekman transport in response to SST gradients

Black: 0 degC/0.04°
Red: 0.02 degC/0.04°
Green: 0.04 degC/0.04°
The magnitudes of surface wind speed and divergence become greater as SST gradient (in °C/0.04°) increases.
Ekman transport dependence on SST gradients

(a) West bound (89.04W, 28.56N)  
(b) East bound (88W, 28.56N)

- Eastward transport at west (east) bound are **linearly** enhanced (weakened) in response to an SST gradient increase;
- There is a net **positive** zonal mass convergence in oil region because of the presence of SST gradients.

(c) North bound (88.44W, 29.04N)  
(d) south bound (88.44W, 28N)

- Southward transport at north (south) bound are **linearly** enhanced (weakened) in response to an SST gradient increase;
- There is a net **positive** meridional mass convergence in oil region, caused by the presence of SST gradients.
Surface momentum roughness length parameterization for seawater and oil

\[ z_{0i} = \left[ \beta_s \frac{0.11 \nu}{u_*} + \varepsilon \left[ \left( \frac{b \sigma}{\rho_w |u_*| u_* \cdot e_i} \right)^2 + \left( \frac{a |u_*| u_* \cdot e_i}{g} \right)^2 \right]^{0.5} \right] \]

(1) Aerodynamical smooth surface \hspace{1cm} (2) capillary waves \hspace{1cm} (3) gravity waves

Parameters: \( \beta_s \), \( \beta_c \), \( \beta_g \) are weights for aerodynamically smooth surface, capillary waves, and gravity waves; \( \nu \) : air molecular viscosity; \( b=0.019 \), \( a=0.035 \), is Charnock’s constant. \( \sigma \) : surface tension. \( \varepsilon=0.25 \) for oil, represents the oil damping effects on capillary waves and short gravity waves; \( \varepsilon=1.0 \) for seawater; \( u_* \) : friction velocity.

Anisotropic: unit vectors parallel (\( e_1 \)) and perpendicular (\( e_2 \)) to the mean direction of wave motions.

References: (1) Nikuradse 1933; Kondo 1975
(2) Bourassa 1999; 2006
(3) Smith et al. 1992
• Binary weights: \( \beta_s = 1 - \beta_c \)

For water surface: \( \beta_c = 0, \beta_g = 0 \) if \( U_{\text{eff}} \leq U_{\text{lim}}, U_{\text{lim}} = 1 \text{m/s} \)

\[
\beta_c = \tanh \left( 0.4 \left( U_{\text{eff}} - U_{\text{lim}} \right)^3 \right), \quad \beta_g = \tanh \left( 0.2 \left( U_{\text{eff}} - U_{\text{lim}} \right)^3 \right) \quad \text{if} \quad U_{\text{eff}} > U_{\text{lim}}
\]

For oil surface: \( \beta_c = 0, \beta_g = 0 \) if \( U_{\text{eff}} \leq U_{\text{lim}}, U_{\text{lim}} = 7 \text{m/s} \)

\[
\beta_c = \tanh \left( 0.4 \left( U_{\text{eff}} - U_{\text{lim}} \right)^3 \right), \quad \beta_g = \tanh \left( 0.3 \left( U_{\text{eff}} - U_{\text{lim}} \right)^3 \right)
\]

\( U_{\text{eff}} = u_* \left[ \ln \left( \frac{z}{z_0} + 1 \right) + \varphi \left( \frac{z}{z_0}, L \right) \right] / K_v \)