Computationally Fast and Accurate Surface Turbulent Fluxes

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1. INTRODUCTION

A theoretical, physically-based model (Bourassa 2006) is used to produce a lookup table for surface turbulent fluxes. The model and lookup table consider dependencies on wind speed, air-sea temperature differences, and directional wave characteristics. The physical impacts of sea state are parameterized through the influences of the surface's orbital motion induced by waves, as well as a vertical displacement of the log-wind profile (displacement height). The considerable input information is reduced to a three-dimensional lookup table. The grid is designed to allow for very rapid interpolation to the transfer coefficient for stress (the drag coefficient), latent heat (or moisture) flux, and the sensible heat flux. This model is well suited to use in applications were there are many calls to the surface flux code, such as numerical weather prediction model and ocean modeling.

2. MODEL PHYSICS

The theoretical flux model (Bourassa 2006) is a combination of the strengths of a variety of flux models. The low wind speed stress is similar to that of the BVW model (Bourassa et al. 1999), which considers three types of roughness elements: smooth surfaces, capillary waves, and gravity waves. The gravity wave part of that model had shortcomings that were dealt with through an improved parameterization of sea state influences (Bourassa 2004). That solution had shortcomings related to very high seas, which were corrected by considering displacement height (Bourassa 2006). The resulting model considered two influences of waves: a lower boundary condition on velocity, related to the orbital motion of the waves, and a vertical displacement related to wind waves. The resulting modeled stresses were well matched to observations form the Storm Wave Study experiment (SWS-2; *Dobson et al.*, 1999; *Taylor et al.*, 1999), which were kindly provided by Peter K. Taylor. The wind speeds in the SWS-2 observations ranged from 2 to 21 ms^{-1} (after quality control), and included a wide range of wave conditions.

The modeled heat fluxes are based on the CFC model (Clayson et al. 1996). This model is founded on surface renewal theory. One parameter was adjusted to a more widely accepted value, correcting an underestimation of the roughness length. This adjustment, and the improved stress-related parameterizations, results in a much better match to high wind speed fluxes, correcting a known deficiency (M. Brunke, personal communication, 2002) of the CFC model.

3. FLUX MODEL EQUATIONS

The fluxes considered in this model are the downward momentum flux ($\boldsymbol{\tau}$), the upward surface turbulent fluxes of sensible (H), moisture (E), and latent heat (Q). Stress can be modeled in terms of the friction velocity ($\mathbf{u}_*$):

$$\boldsymbol{\tau} = \rho\, \mathbf{u}_* \,|\, \mathbf{u}_* \,|, \qquad (1)$$

where ρ is the density of the air. Sensible heat, moisture flux, and latent heat are

$$H = -\rho\, C_p\, \theta_* \,|\, \mathbf{u}_* \,|, \qquad (2)$$

$$E = -\rho\, q_* \,|\, \mathbf{u}_* \,|, \qquad (3)$$

$$Q = -\rho\, L_v\, q_* \,|\, \mathbf{u}_* \,| = L_v\, E, \qquad (4)$$

where θ_* and q_* are scaling parameters analogous to u_*, C_p is the specific heat of air, and L_v is the latent heat of vaporization.

The direct influence of surface waves on flux and airflow characteristics ($\mathbf{u}_*$ and z_o) is determined by the relation between $\mathbf{u}_*$ and roughness length (z_o). Given $z_o(\mathbf{u}_*)$ and the modified log wind relation $\mathrm{U}(z)$, where z is the height above the local mean surface, it is possible to iteratively solve for $\mathbf{u}_*(\mathbf{U})$ and $\boldsymbol{\tau}(\mathbf{U})$. The modified log–wind relation is

$$\mathbf{U}(z) - 0.8\mathbf{U}_{orb} - \mathbf{U}_{curr} = \frac{\mathbf{u}_*}{\kappa}\left[\ln\left(\frac{z - H_{wind}}{z_o} + 1\right) + \varphi(z, z_o, L)\right], \qquad (5)$$

where k is von Kârmân's constant, d is the displacement height (the height at which the log wind profile extrapolates to zero wind speed), and L is the

Monin-Obukhov stability length. The influence of atmospheric stratification in the boundary-layer is modeled through the Monin-Obukhov stability length (Liu et al.*,* 1979). The profiles of potential temperature (θ) and specific humidity (q) have functional forms similar to the log-wind profile.

$$\theta(z) - \theta_s = \frac{Prt\,\theta_*}{k}\left[\ln\left(\frac{z}{z_{o\theta}} + 1\right) + \varphi_\theta\left(z, z_{o\theta}, L\right)\right] \quad (6)$$

and

$$q(z) - q_s = \frac{Sct\ q_*}{k}\left[\ln\left(\frac{z}{z_{oq}} + 1\right) + \varphi_q\left(z, z_{oq}, L\right)\right], \quad (7)$$

where *Prt* is the turbulent Prandtl number, and *Sct* is the turbulent Schmidt number. The parameters *Prt* and *Sct* are often used to tune the gain of flux models (i.e., $\partial E/\partial(q - q_s)$ and $\partial H/\partial(\theta - \theta_s)$). The parameterization of momentum roughness length is described in Bourassa (2006), and the roughness lengths for potential temperature ($z_{o\theta}$) and specific humidity (z_{oq}) are adapted from the surface renewal model of Clayson et al. (1996). The parameterization of L is identical to that used in the BVW (Bourassa-Vincent-Wood) flux model (Bourassa et al., 1999), the CFC (Clayson-Fairall-Curry) model (Clayson et al. 1996), and Bourassa (2003).

4. WAVE INFLUENCES ON FLUXES

One input to the model should be the wave-relative wind, in vector components, and the height corresponding to this wind. That is, the wind speed minus the current and the wave's orbital velocity. Many NWP models include wave information from which the orbital velocity of the dominant waves can easily be extracted. Assuming a value of zero for the orbital velocity results in slight overestimations of the fluxes. The observation height should also be modified by subtracting 80% of the height of the dominant wind waves. With these two consideration, the model accounts for directional wave influences on fluxes. In theory, this approach would also include changes in wave characteristics and fluxes associated with shallow water.

The wave data can often be ignored; however, this will introduce small biases, which might be important for climate modeling. For applications involving large waves, the wave considerations can be very important, and should not be ignored.

The model lookup tables are based on transfer coefficients, which the model combines with the input data to determine the surface turbulent fluxes. The lookup table is designed so that the lookup table indices can be determined with one computationally fast calculation for each index. Tri-linear interpolation is used to interpolate between grid points. The three axes are surface relative wind speed, difference in atmospheric and surface potential temperature, and reference height relative to the wave disturbed surface. Note that the height considerations allow input data from between 2 and 40m.

5. ADDITIONAL FLUX MODEL INPUT/OUTPUT

Additional input requirements are a sea surface temperature, air temperature and specific humidity with the corresponding height corresponding to these observations, and surface pressure.

The model output data are vector stress components (Nm^{-2}), sensible heat flux (Wm^{-2}), and latent heat stress (Wm^{-2}).

6. CLOSING COMMENT

This lookup table version of the flux model is now used to product the FSU winds and fluxes. The analysis scheme highly iterative, particularly when used to objectively determine weighting parameters. The use of this new flux model resulted in an increase in processing speed, despite replicating a much more complex model of surface fluxes.

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