Examining effects of moisture exchange feedback in a bulk heat-flux model

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Introduction

Modern numerical weather and climate prediction models do not attempt to represent physical processes that occur over short time and spatial scales. Errors may accumulate from slight inaccuracies in microphysical processes that wildly change the synoptic result, or it may be too computationally expensive to attempt to simulate these processes in models that must be run frequently to remain up to date. Instead, these processes are parameterized—replaced with simplified representations using bulk averaged values of the properties of the atmosphere at a location.

One process is the interaction between the air and sea surface, including the transfer of energy through solar radiation and heat. Heat energy can be transferred from the sea to the air by latent heat, the energy required to complete a phase change which is absorbed during evaporation and released during condensation. Because this process is dependent on the rate of evaporation, which is proportional to the difference between the specific humidity at the surface and the saturation humidity (Figure 2), and because the rate moisture is added to the atmosphere is dependent on the evaporation rate, there is a negative feedback on latent heat flux as the air at the ocean surface reaches saturation. Modeling these feedbacks is important to understanding the numerical models' sensitivity to computed heat flux from bulk algorithms (Reeves Eyre et al., 2021).

The purpose of this project was to create a program that integrated the Coupled Ocean-Atmosphere Response Experiment (COARE) bulk heat flux algorithm over time to allow for analysis of how initial conditions and parameters affect flux with a focus on evaporated moisture and its contribution to the saturation of air at the sea surface in the environment of a tropical cyclone.

Methods and Materials

The COARE algorithm computes sensible and latent heat fluxes given static bulk variables. The algorithm's principles and verification are detailed in Fairall et al. (1996). First, the algorithm from this paper was implemented in C using the GCC compiler in Visual Studio Code. A flowchart of the process the program follows is given in Figure 1. The algorithm uses a loop to converge from initial guess values to reasonable approximations of sensible and latent heat flux over the sea surface, accounting for turbulence and atmospheric instability according to Figure 2. Then, this algorithm was enclosed in a loop to iterate over time, with calculated fluxes being allowed to modify the next iteration's bulk value for humidity according to Figure 3. This program was then enclosed by another program to generate datasets of time sequences with a range of initial bulk values for windspeed and parameters. Calculated values for each step and summary results were written to a text file.

Results

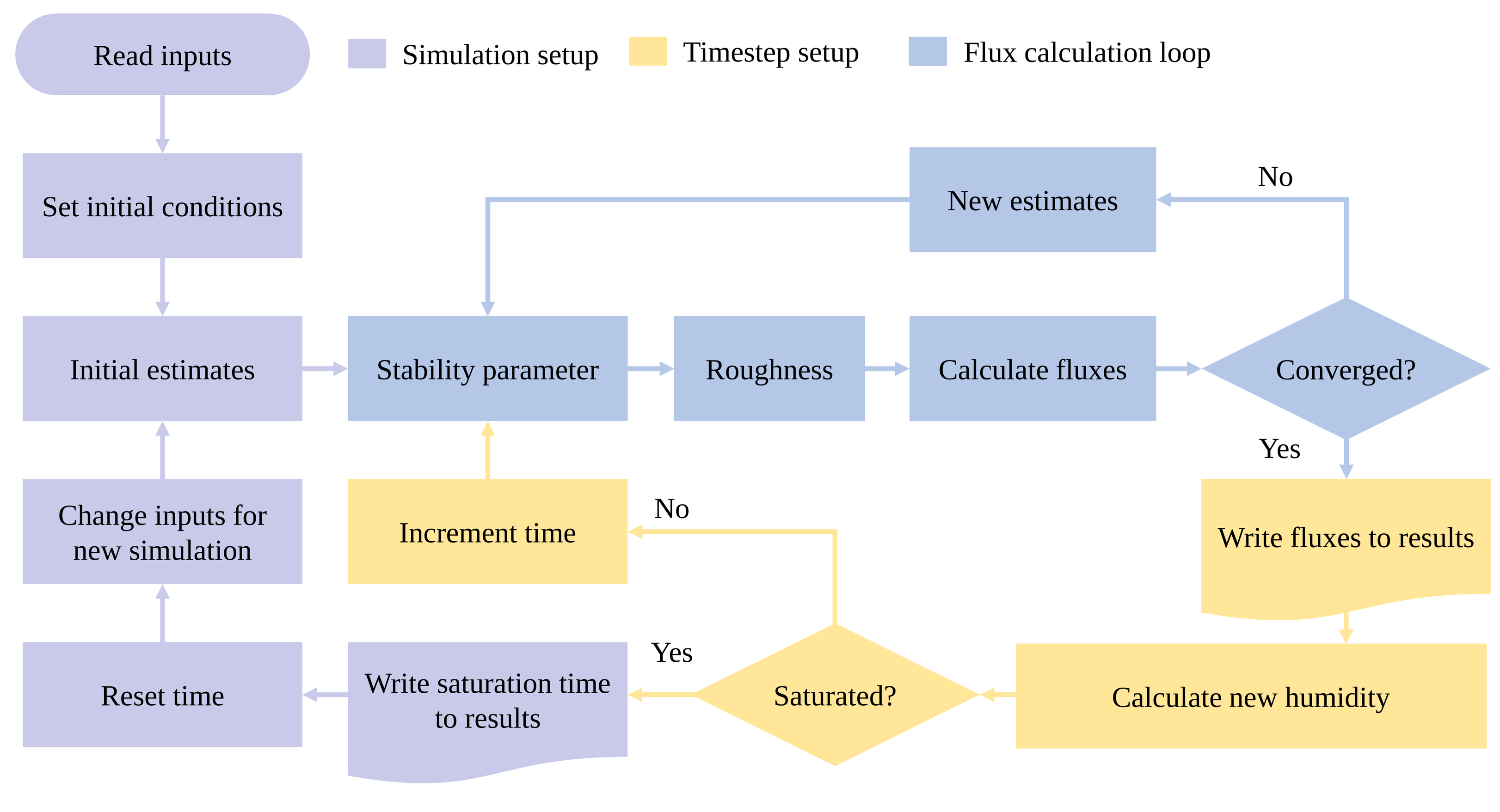


Figure 1 (above): A flowchart of the program.

$$H_L = \rho_a L_v C_{en} S_r (Q_s - Q_r)$$

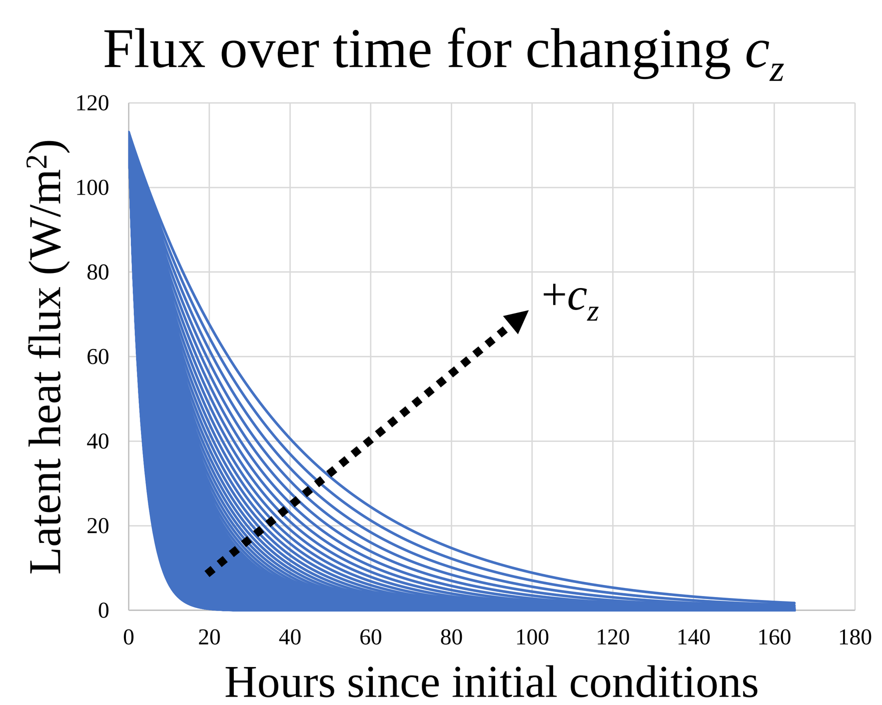
Figure 2 (above): Relates latent heat flux (H_L) to the air density (ρ_a), enthalpy of vaporization (L_v),transfer coefficient (C_{en}), horizontal wind parameter (S_r), saturation humidity (Q_s), and measured humidity (Q_r) (Fairall et al., 1996).

Figure 3 (below): Relates the rate of increase in specific humidity to the calculated latent heat flux (H_L), enthalpy of vaporization (L_v), air density (ρ_a), height of volume (z), and coefficient of integration of vertical distribution of moisture (c_z). A watt is defined as 1 joule per second.

$$dQ\left(\frac{\mathrm{kg}}{\mathrm{kg}\times\mathrm{s}}\right) = c_z H_L \left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) \Big/ \left[L_V\left(\frac{\mathrm{J}}{\mathrm{kg}}\right) \times \rho_a \left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right) \times \mathrm{z}\ (\mathrm{m})\right]$$

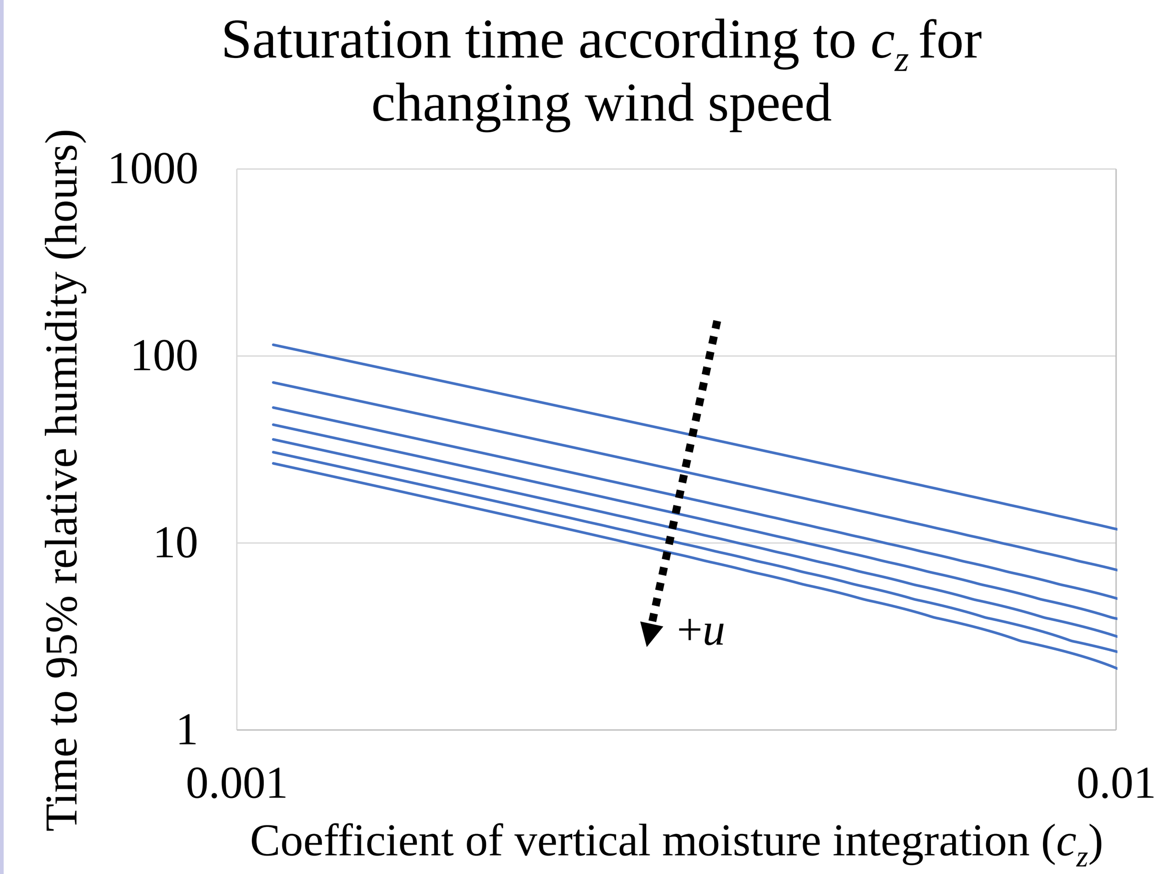
The completed program was used to generate simulations of the evaporation-humidity feedback as calculated using the COARE algorithm given an input file with a range of initial conditions to test, including wind speed, humidity, temperature, and program instructions such as the lengths of time for the simulation and each simulation step.

Because the distribution of evaporated moisture vertically through the simulation volume is unknown, the proportion remaining at the surface was approximated with an unknown but determinable coefficient c_z. A graph of fluxes over time for a range of values of c_z was created (Graph 1).



Graph 1: Each line represents a simulated time sequence of calculated fluxes as the air became saturated. Values of heat flux remain greater at times past hour 0 with increasing values of c_z.

Conclusions



Graph 2: This chart maps the time each simulation took to reach saturation against the c_z value used. Each line is a set of simulations run with a given wind speed u and changing c_z. Lines from highest to lowest represent wind speeds from 2 m/s to 14 m/s.

The program successfully implemented the COARE algorithm and produced initial results that match COARE data from the R/V *Moana Wave*. The program is efficient for its current tasks, completing the calculations for Graph 2 (700 simulations of up to 120 hourlong steps) in 51 seconds on a home laptop computer. Following the initial timestep, the calculated flux decreased as humidity reached saturation, in accordance to known physical laws. The timespan on which this occurred, however, was dependent on the integrated moisture distribution. The simulation data indicated inverse relationships between c_z and wind speed and saturation time. The program created could be finetuned using real-world data over time to create an expression to calculate this coefficient based on atmospheric conditions such as turbulence and buoyancy (Hourdin et al., 2017). With this in hand, the negative feedback loop explored in this program could be more thoroughly examined for its effects in numerical weather and climate models through simulation analysis such as in Reeves Eyre et al. (2021).

References

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