U.S. DEPARTMENT OF ENERGY
SciDAC Scientific Discovery through Advanced Computing

Analyzing the stability of flux coupling methods with a simple atmospheric boundary layer model

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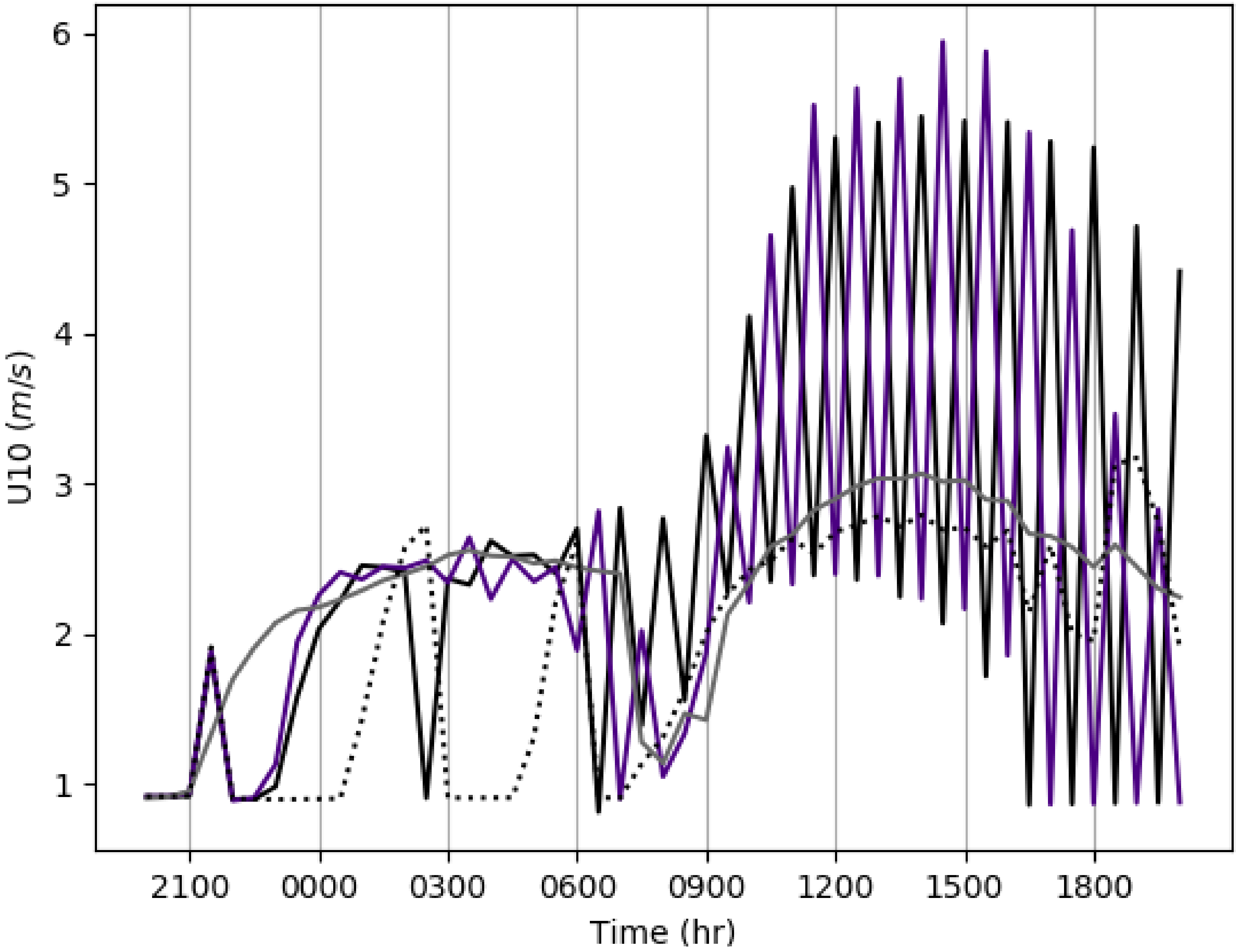
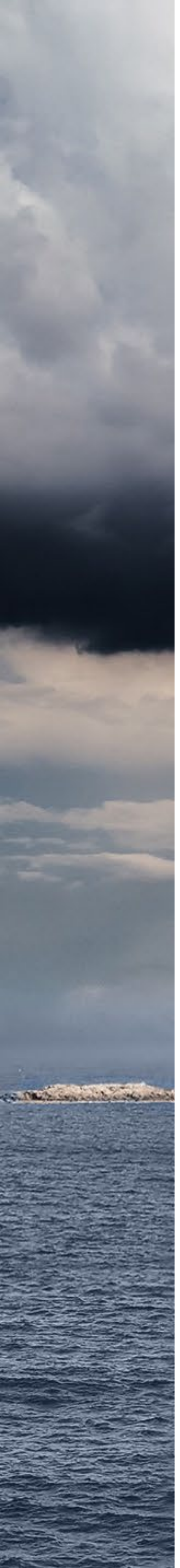
A bit of history

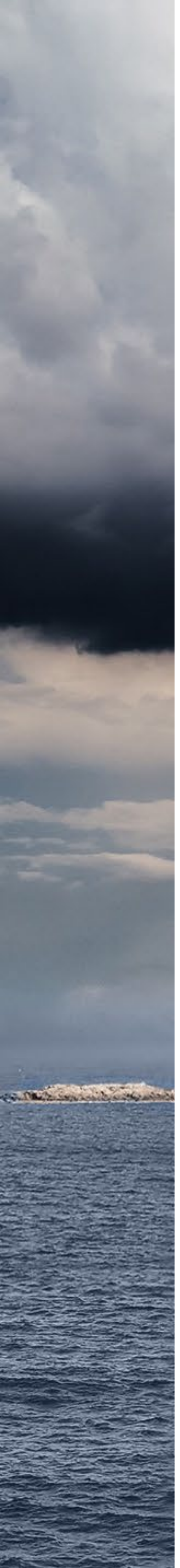
- In early 2021, I noticed some odd "fog" in the boundary layer over the Amazon in some E3SMv1 runs.
- Investigating this a bit further, it became clear that near-surface wind was oscillating wildly in this region.
- Dynamics and PBL scheme dominate budget.
  - Black = default settings
  - Purple = 10s "macmic" Δt
  - Grey = 10s atm Δt
  - Dotted = "srf_flux_avg"





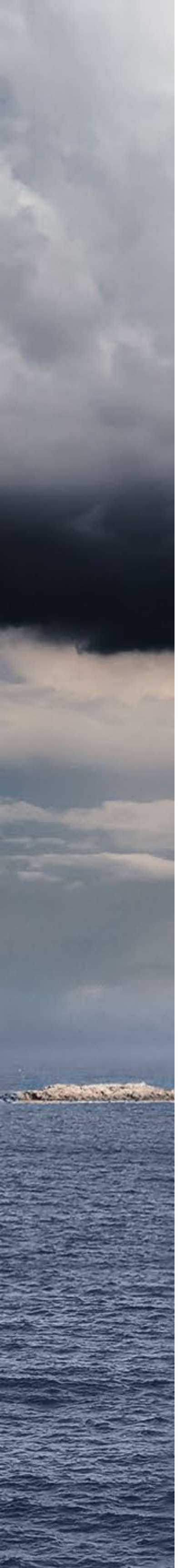
What's the cause? Many initial hypotheses…

1. This behavior is due to some kind of previously undiscovered bug.
   - "Unknown bug" is not specific enough to be falsifiable. (But specific bugs were found.)
2. Numerical instability due to a specific process internal to the atmosphere having a coarse time step, specifically CLUBB or the dynamics.
   - Pretty much immediately ruled out; already had data from short time step runs.
3. Numerical instability related to process coupling within and between the atmosphere and land models overall.
   a) Could be related to the atmosphere's process order, i.e. coupler, dynamics, then PBL scheme vs. coupler, PBL scheme, then dynamics.
   b) Could be related to the coarse atmosphere-land coupling step.
4. Numerical instability in the iterative solver(s) diagnosing surface energy balance in the land model.
   - Quickly ruled out a simple "too few iterations" issue, though other possibilities exist.



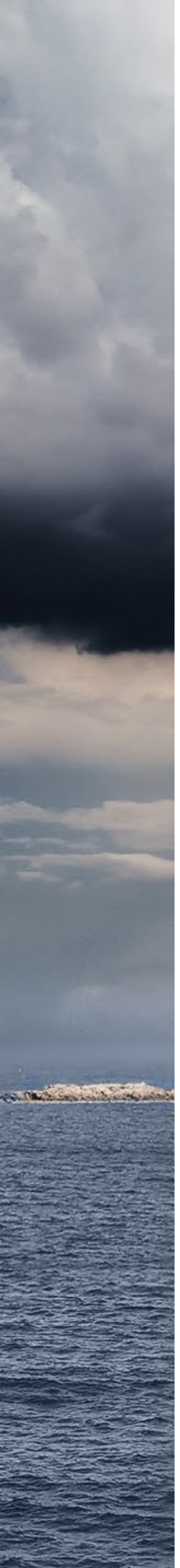
Further developments

- The oscillations are regime- and location-dependent. Worse when:
  - Surface is rougher (mountains, forests).
  - Surface is colder - boundary layer is convectively stable.
  - Wind speed is higher.
  - Atmosphere’s vertical resolution is finer (worse for EAMv1 than CAM5).
- An E3SM-specific bug was found in the gustiness parameterization; it produced a discontinuity in surface stress at low wind speeds.
  - Fixing this bug removed oscillations at small time step sizes, but also increased near-surface wind speed, so it made the problem worse at default settings!
- Hacked together an “implicit” atmosphere-land coupling scheme.
- Changed process order of CLUBB and dynamics.
  - Helped, particularly combined with “implicit” mods. But also affects wind speeds.



Solutions to date

- The most effective solutions have involved two types of changes:
  - Change process order to run CLUBB before dynamics.
  - Avoid explicit flux coupling OR update stress more frequently.
- E3SM prototype:
  - Use implicit predictor-corrector method to calculate the stress.
  - Then move CLUBB to before dynamics.
    - ✓ Unfortunately, changing process order changes climate and intermittently crashes, possibly requiring retuning or other numerics changes.
- CAM solution:
  - Move CLUBB to before dynamics (tphysac).
  - Update momentum fluxes every CLUBB time step.
    - ✓ Does not conserve momentum over ocean.
- AM4-CLUBB: updating momentum fluxes more frequently improves wind field.



Questions to answer

- What time step size do we need to use to avoid this issue, anyway?
- Why exactly does process order matter?
  - Standard explanation: mismatch between winds where surface fluxes are calculated, versus where applied, is bad.
  - But how does this cause oscillatory behavior?
  - Is using a different process order actually necessary to fix this problem?
- Why does the problem occur at all?
  - Want some kind of simplified test case to reproduce this.
  - Want to know if future models or numerical methods will encounter this problem.

Simplified boundary layer model

- Proposed 1D model using a complex number $s = u + iv$ to represent winds:

$$\frac{\partial s}{\partial t} = K\frac{\partial^2 s}{\partial z^2} - \left(\frac{1}{\eta} + if\right)(s - u_g)$$

  - K is eddy diffusivity, η is a dynamics timescale, f is the Coriolis parameter, u_g is geostrophic wind
- Boundary conditions:

$$\lim_{z \to z_{bot}} -K\frac{\partial s}{\partial z} = \frac{\tau\left(s(z_{bot})\right)}{\rho}$$

$$\lim_{z \to \infty} s = u_g$$

  - Where $\tau(s)$ is stress as a function of the surface wind.
- Initial condition:

$$s\Big|_{t=0} = s^0(z)$$

Analytic results

- We can introduce the effect of explicit flux coupling by holding τ constant over a given time step.
- By linearizing τ around the steady state solution, we can analytically solve for surface winds over multiple time steps, and do stability analysis.
- This gives an analytic bound for the maximum stable time step:

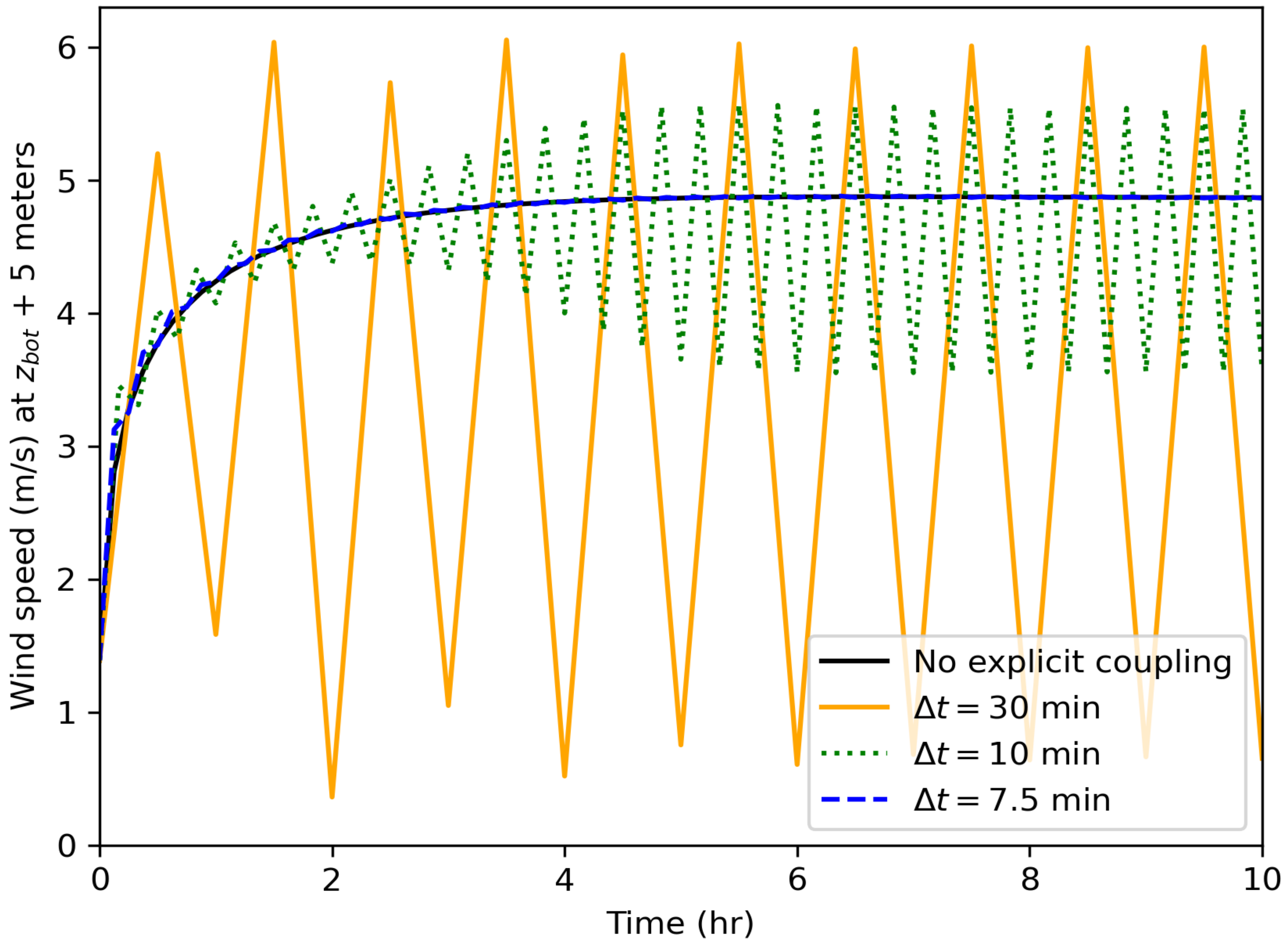
$$\Delta t < \eta \left[\mathrm{erf}^{-1} \left(\frac{\sqrt{K}\rho}{\sqrt{\eta} \left(\frac{d|\tau|}{d|s|} \right)} \right) \right]^2$$

  - Valid at equator; if $f \neq 0$ the expression is much more complicated.
- Since this is a little unwieldy to evaluate, there is a simpler, weaker bound:

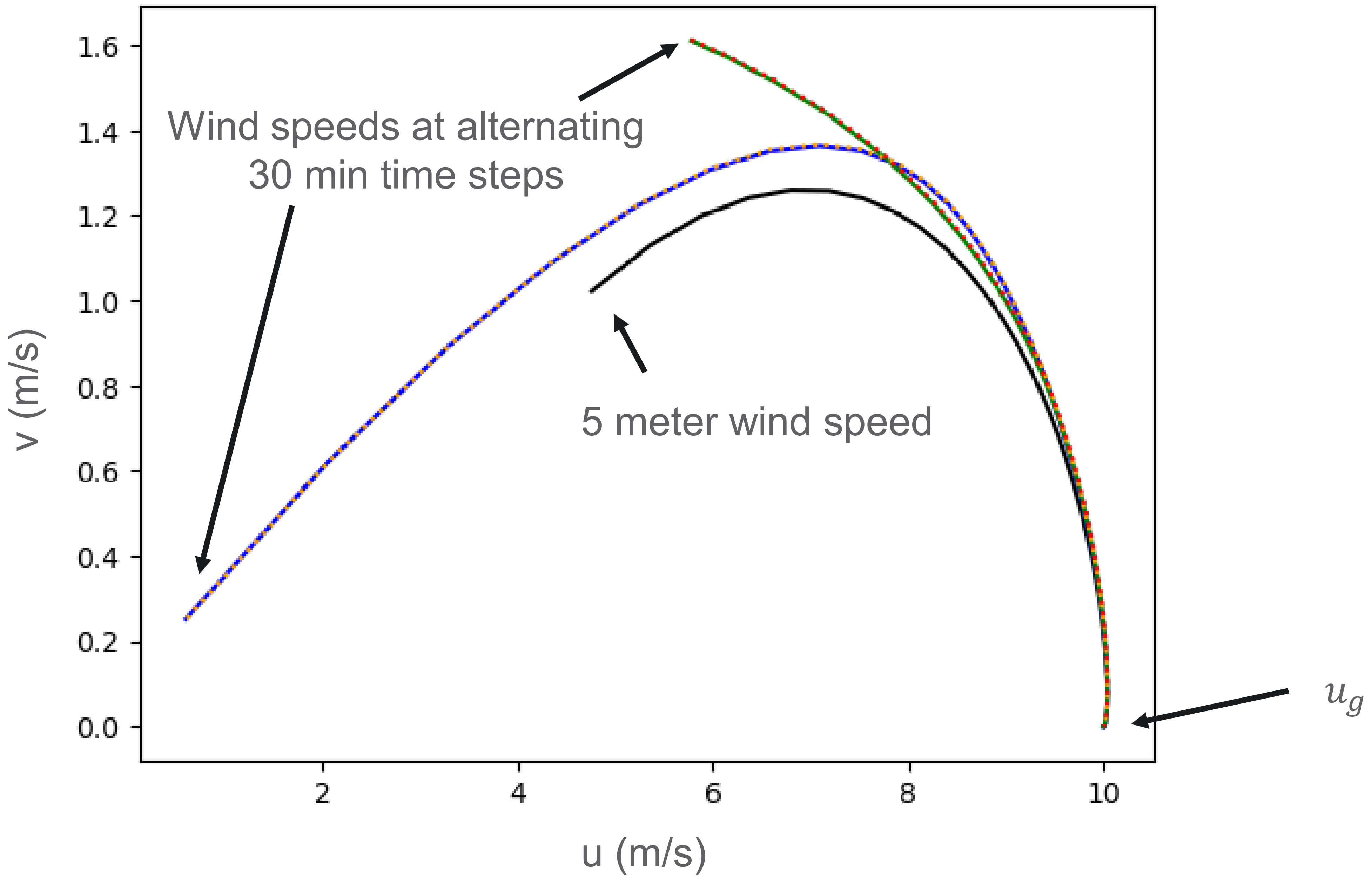
$$\Delta t < \frac{K}{\pi \left(u_* \frac{du_*}{du_{bot}} \right)^2}$$

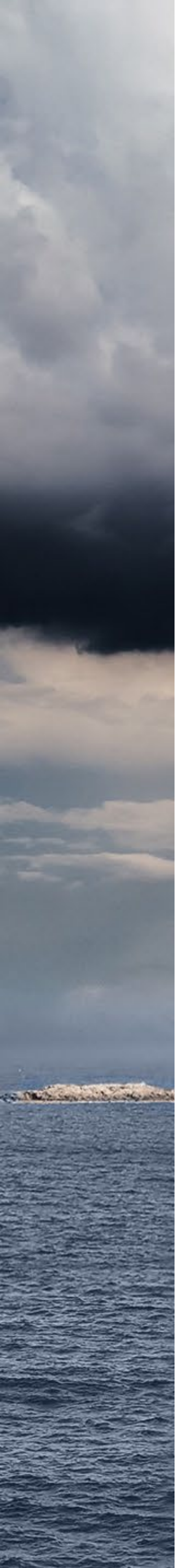
Reproducing oscillatory behavior

- Numerically, we can also reproduce the oscillations.
- Demonstrates that this problem can be (qualitatively) reproduced with no sequential splitting (hence no process order).
- This gives us a test problem to try different numerical methods on.

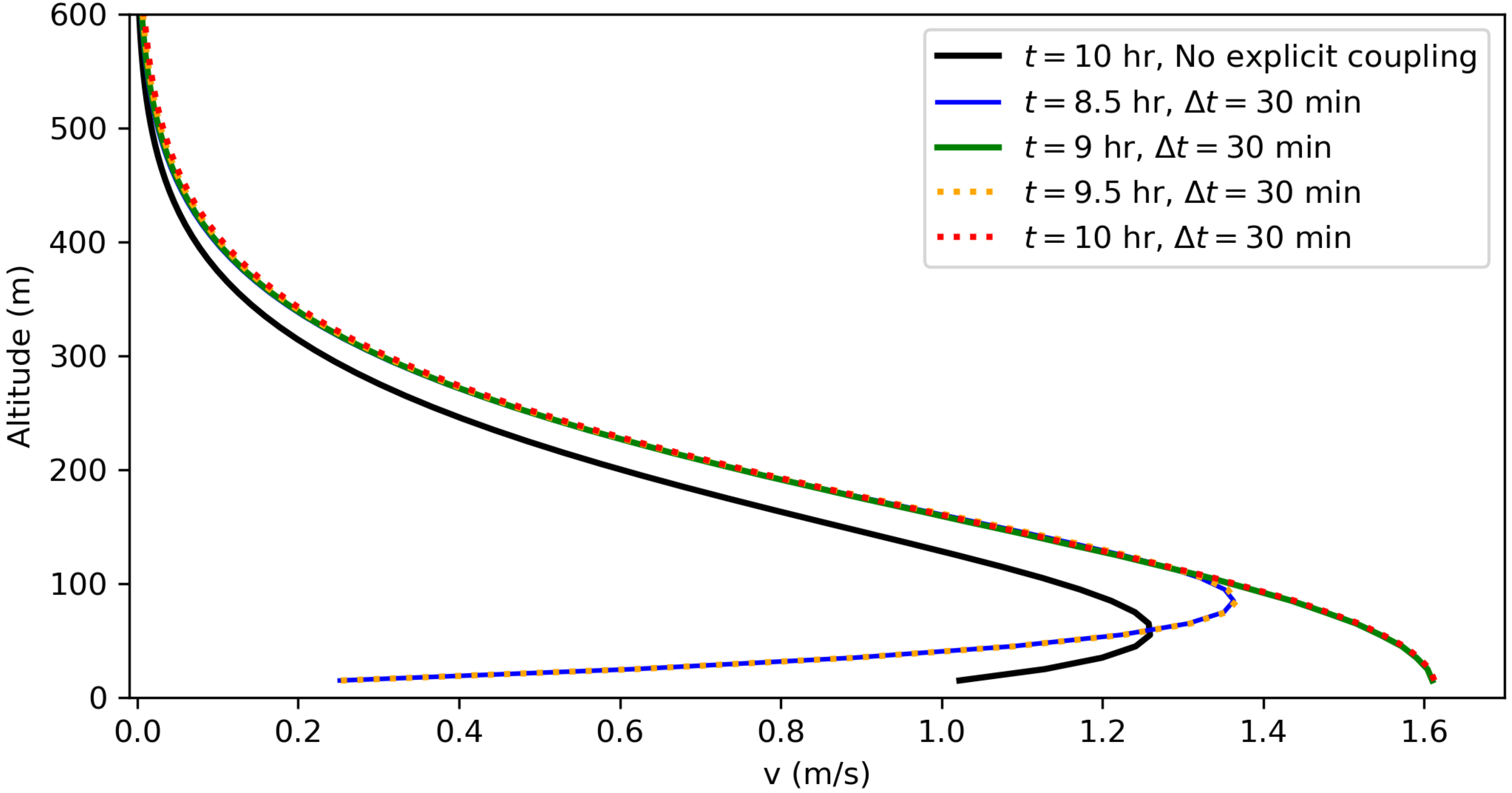


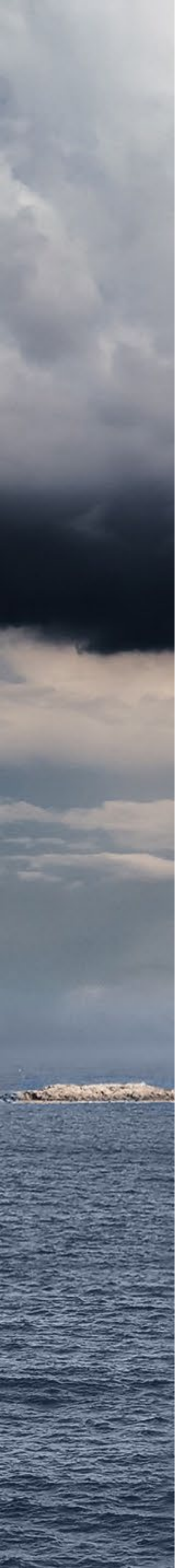
Wind profiles produced by model





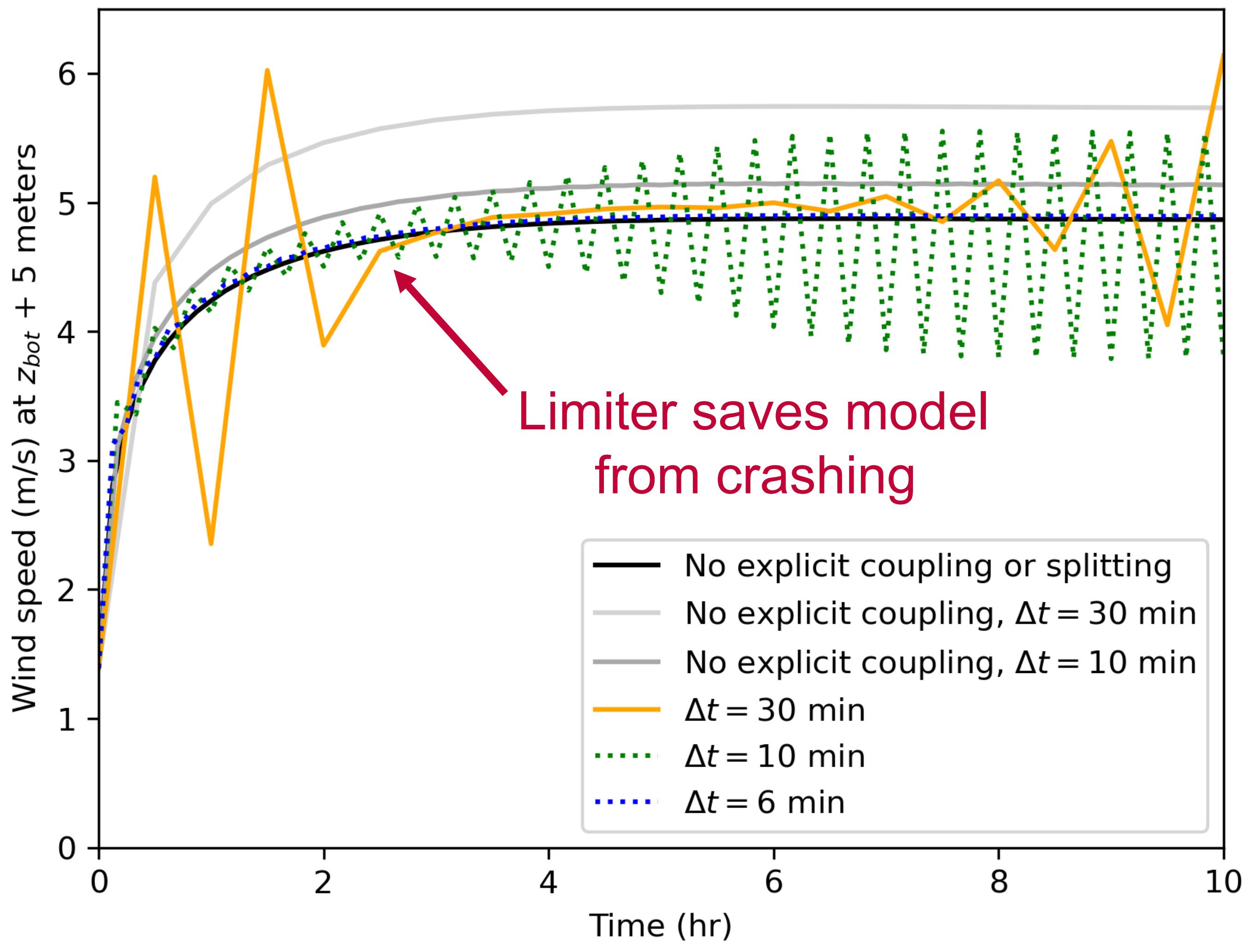
Wind profiles produced by model



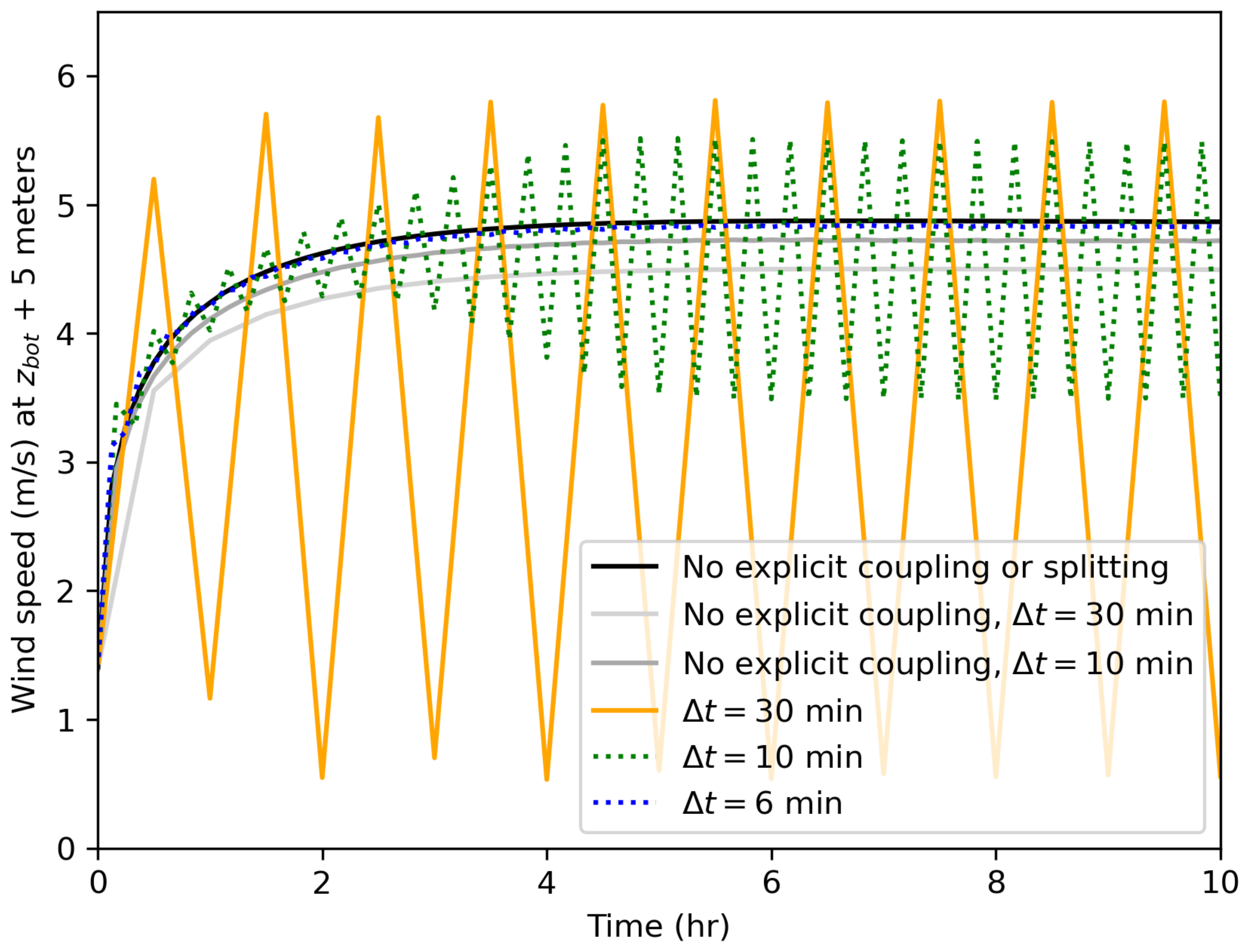


Comparison of sequential split methods

Vertical diffusion before dynamics

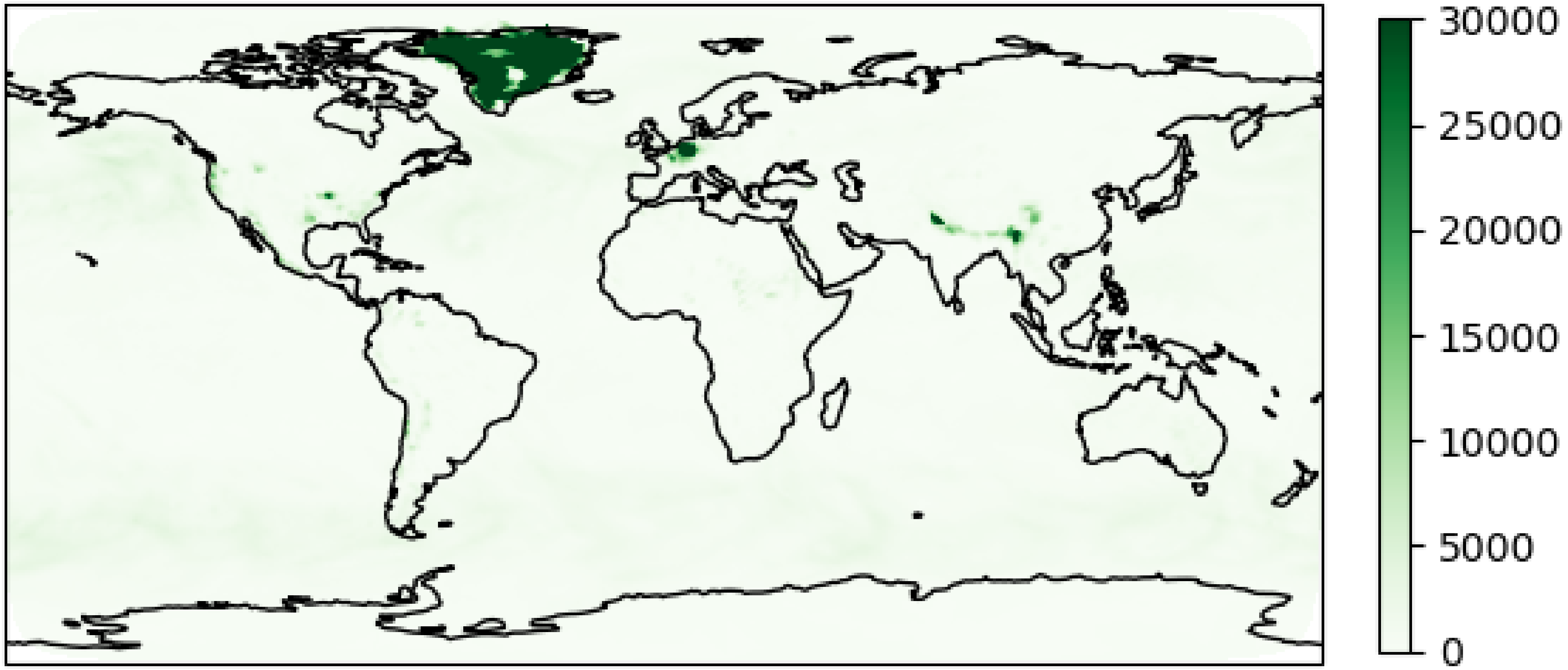


Vertical diffusion after dynamics



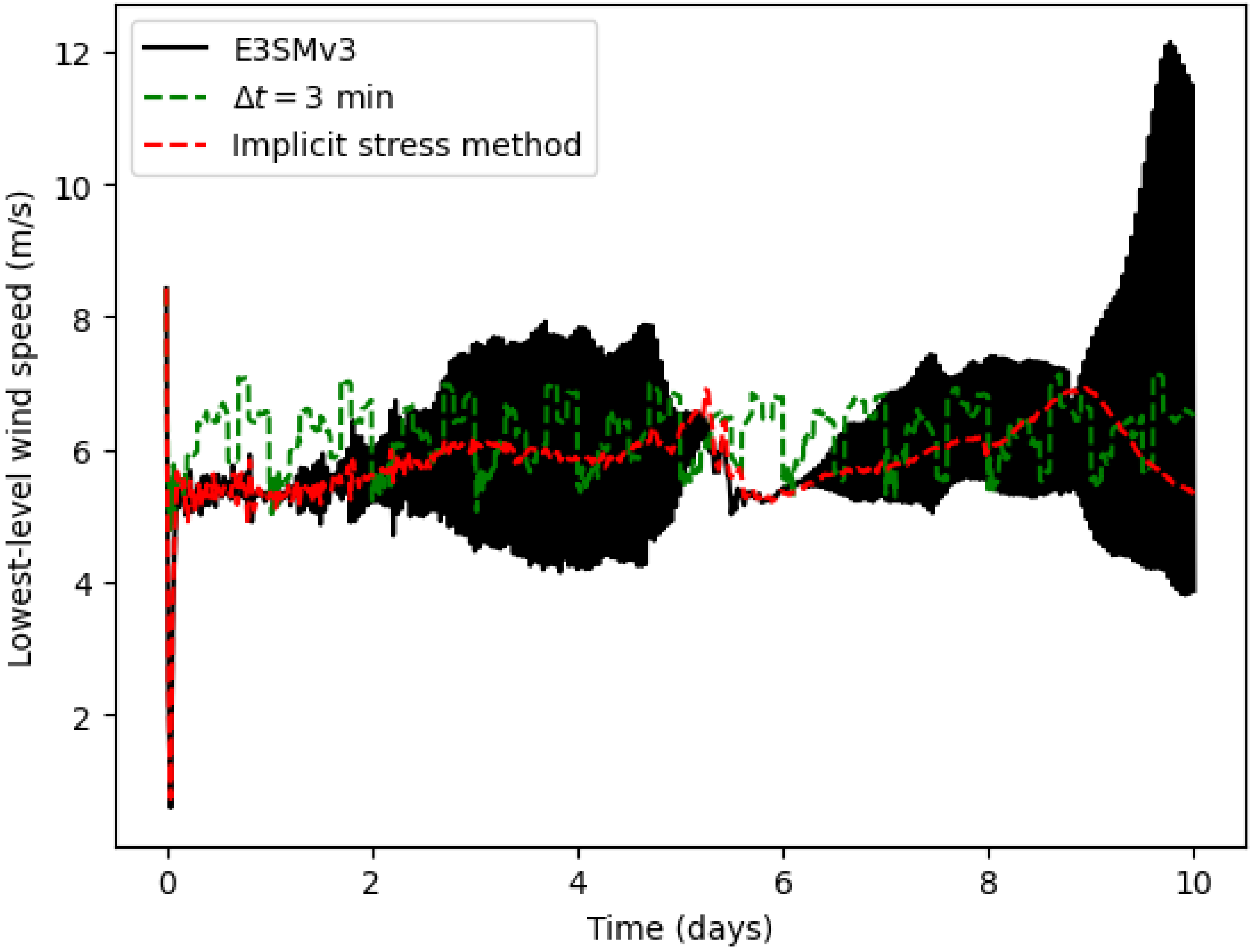
Preliminary results for improved numerics

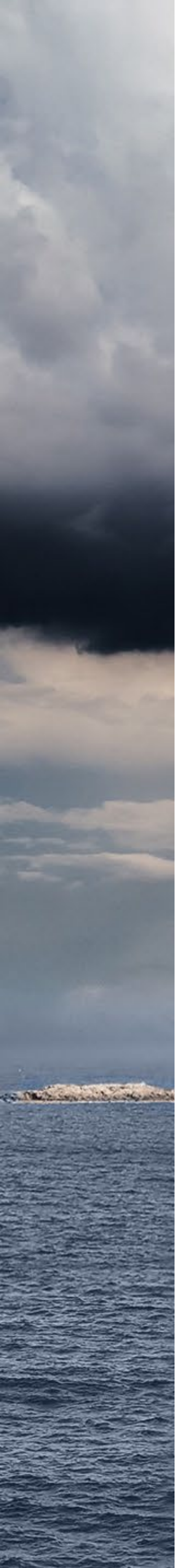
- Early testing: run E3SMv3 for 10 days, outputting wind every time step.
- Look at estimated power spectral density of wind time series at $2\Delta t$.
  - $3 \times 10^4 m^2/s$ is about the magnitude of the diurnal cycle over most of the globe.



Tested interventions

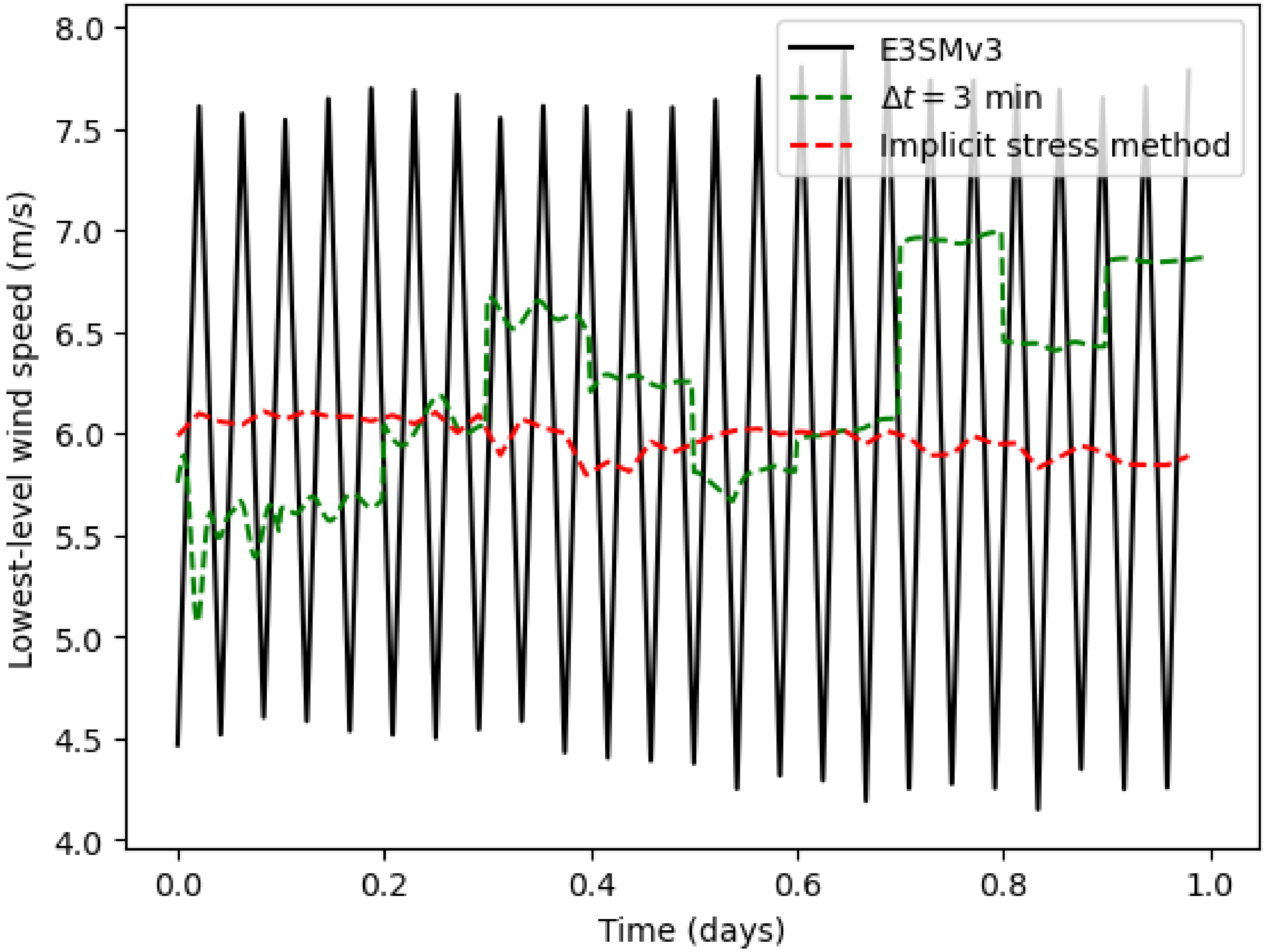
- Two tested changes:
  - Reduce model time step to 3 min.
  - Use implicit method to set stress based on a linear approximation of the PBL scheme.
- Both are effective at removing oscillations (graph on left is at a point in Greenland).
- Model time step reduction is obviously too expensive, but diurnal changes are themselves interesting.

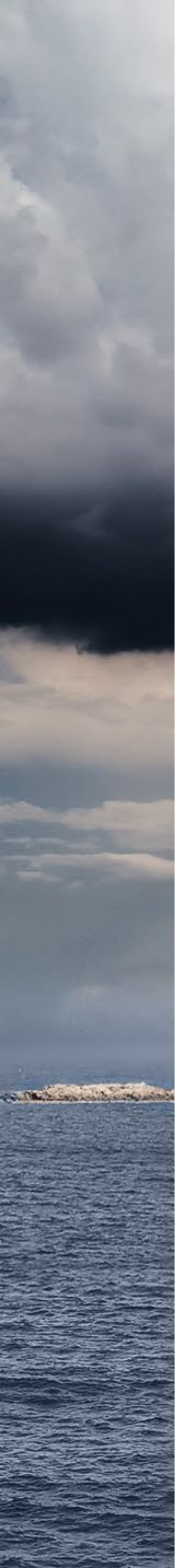




Tested interventions

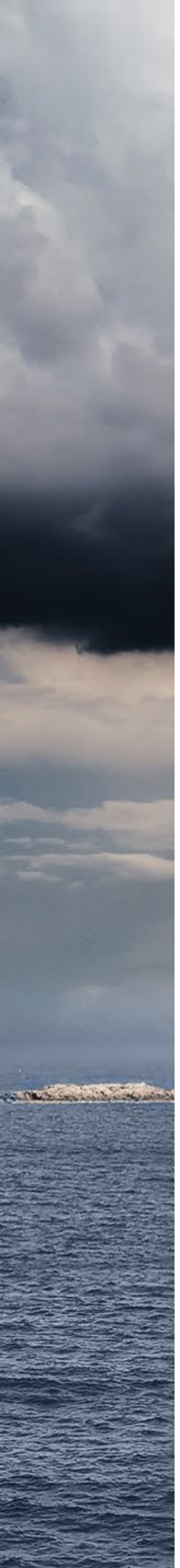
- Same as previous slide, except zooming in on day 4





Ongoing and future work

- Testing additional interventions.
  - Recalculate surface fluxes within CLUBB loop.
    - ✓ With or without ”corrections” to improve conservation of momentum.
  - Simpler variations of implicit method code.
  - Implicit method for energy fluxes, not just momentum.
- Interaction with vertical grid
  - Have some simplified model results, but not yet experimenting with EAMv3 directly.
- Change CLUBB numerics?
  - In an ideal world, would want second-order coupling between land and atmosphere, but this is not trivial
- Testing climate impact.
  - Does the implicit method improve wind speeds?
  - What happens in the fully coupled model (e.g. to SSTs, sea ice)?



Thank you

Work performed as part of the PAESCAL SciDAC-5 project at PNNL.