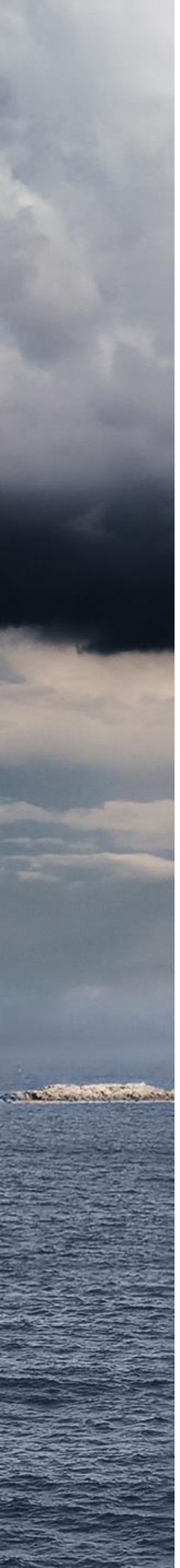

U.S. DEPARTMENT OF ENERGY

SciDAC Scientific Discovery through Advanced Computing

Paths to numerically stable and momentum-conserving atmosphere-surface coupling in E3SM

April 25, 2025

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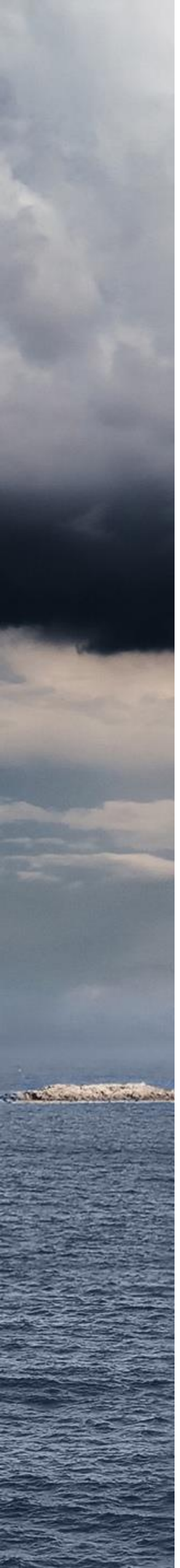
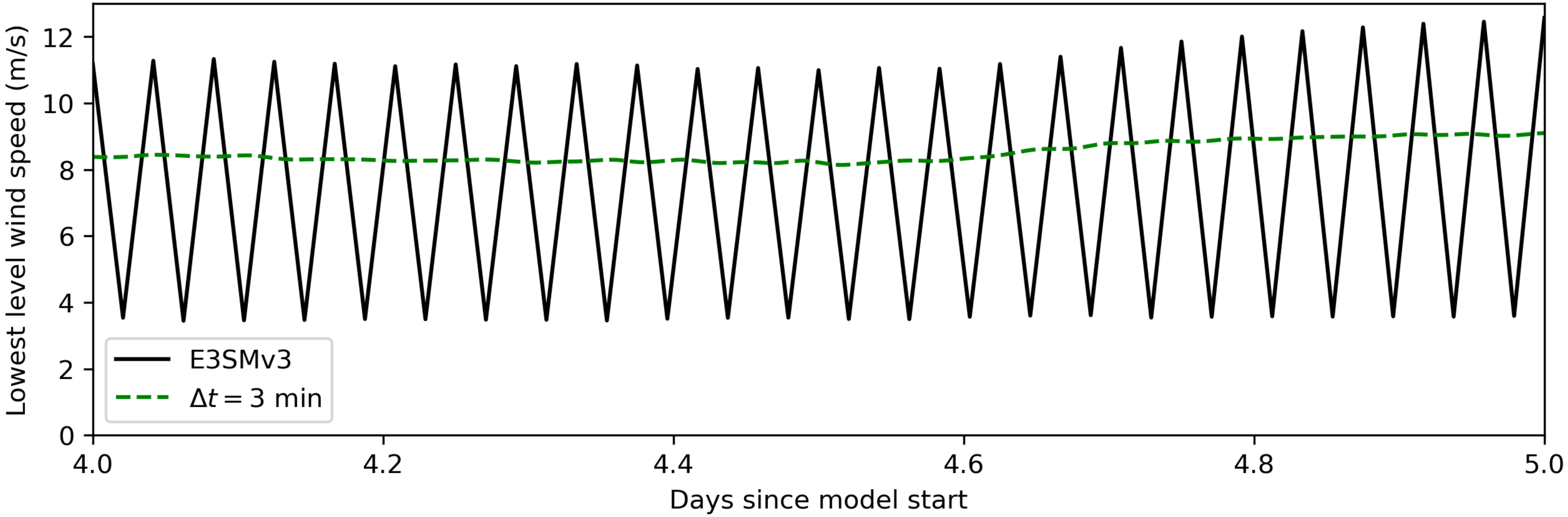
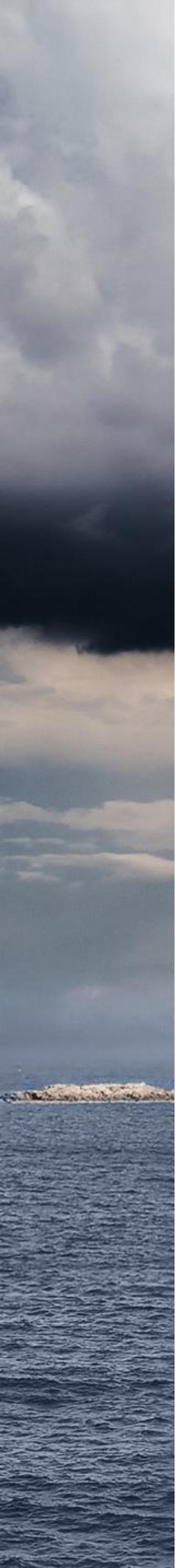


Spurious oscillations in near-surface winds



- Boundary layer winds over land in E3SM often oscillate with a period of $2\Delta t$, where Δt is the model time step.
- Above is an example column with severe oscillations (over Greenland).
- Oscillations apparently due to numerical instability, not present for small Δt.

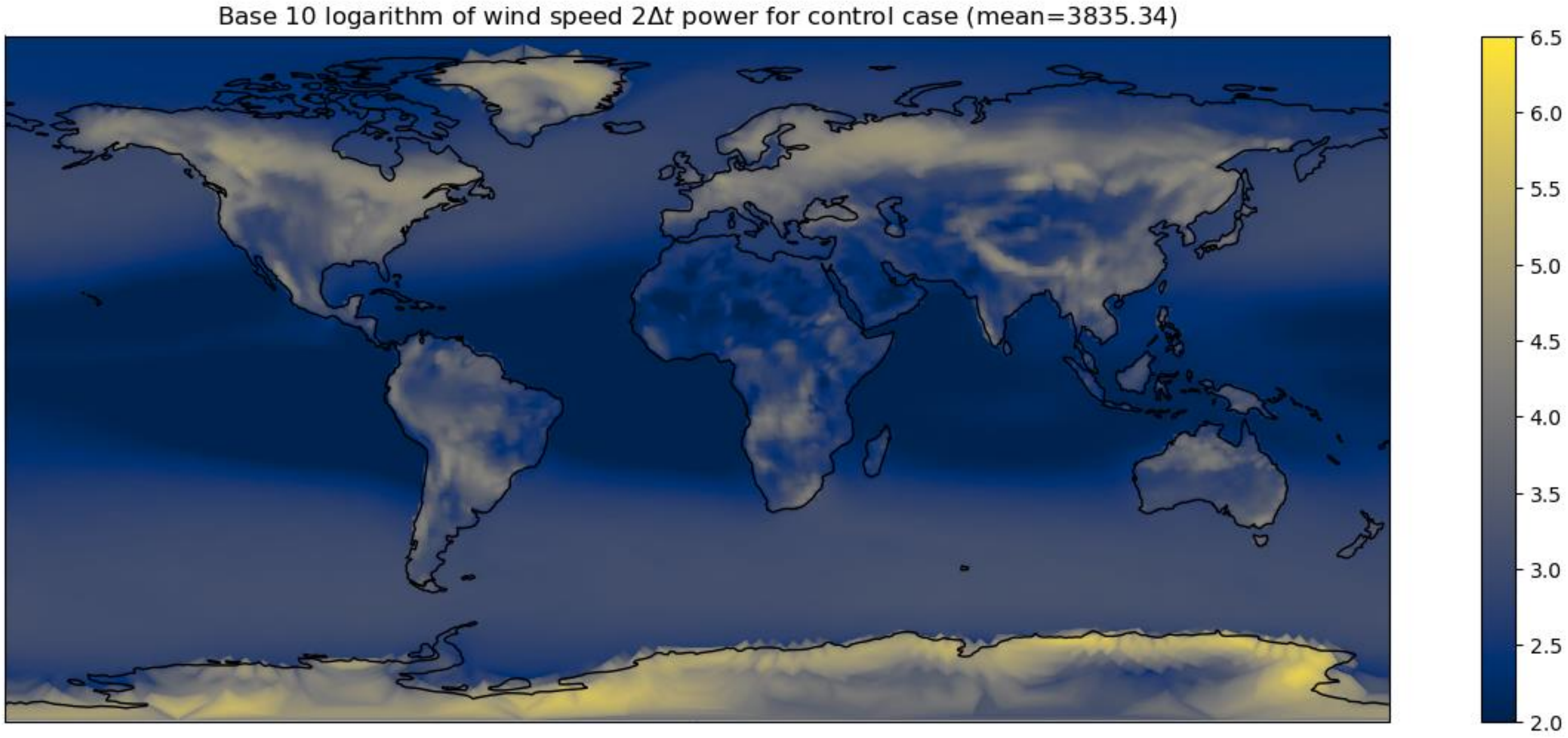


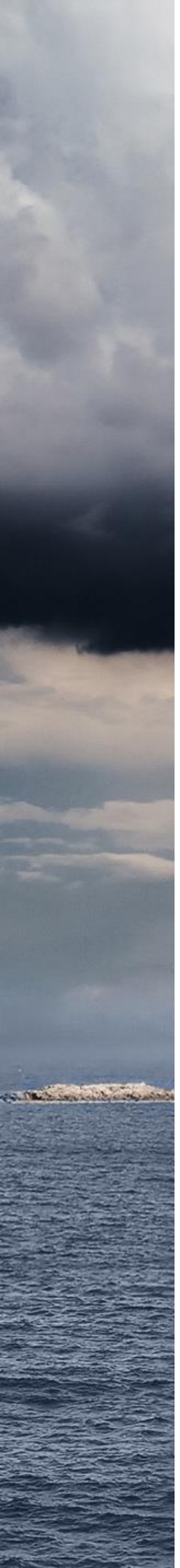
When have these oscillations occurred?

- Issue noticed over Antarctica long before first version of E3SM (CAM4/CAM5).
  - Not severe, a temporal smoothing option was added to reduce this, but not used.
- Issue rediscovered in E3SMv1 over South America.
  - More severe in E3SMv1, apparently due to higher vertical resolution in boundary layer.
- Issue persists in E3SMv3, though appears less severe in tropics.
  - Reason not known, may be tuning differences or gustiness bug fixes
- Common in stable boundary layers where the surface is rough or wind is high.
  - Very strong/common over land ice: Greenland/Antarctica
  - Nocturnal boundary layer over mountains, sometimes forests
  - No major issues over ocean or sea ice for low res F cases
    - ✓ Might be issues for high res cases if strong TCs can form - unclear

Susceptible locations in E3SM

- Can use Fourier-transform-based diagnostics to look for where oscillations are most severe.
  - Note log scale; severe oscillations only occur in yellow areas.
  - This and other global results are from 9 years of an F2010 compset





Understanding with a 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:

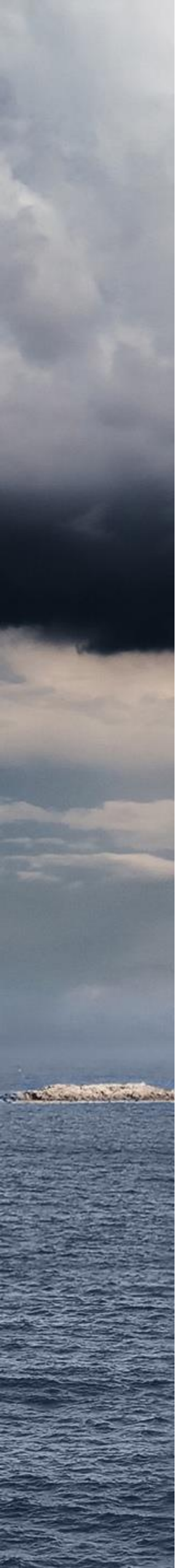
$$\lim_{z \to z_{bot}} -K\frac{\partial s}{\partial z} = \frac{\tau\left(s(z_{bot})\right)}{\rho}$$

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

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

- Initial condition:

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



Analytic results

- Can modify the equations by only updating surface stress at a fixed time step Δt, emulating the effect of E3SMs explicit flux coupling.
- If $f = 0$, an analytic bound for the maximum stable time step:

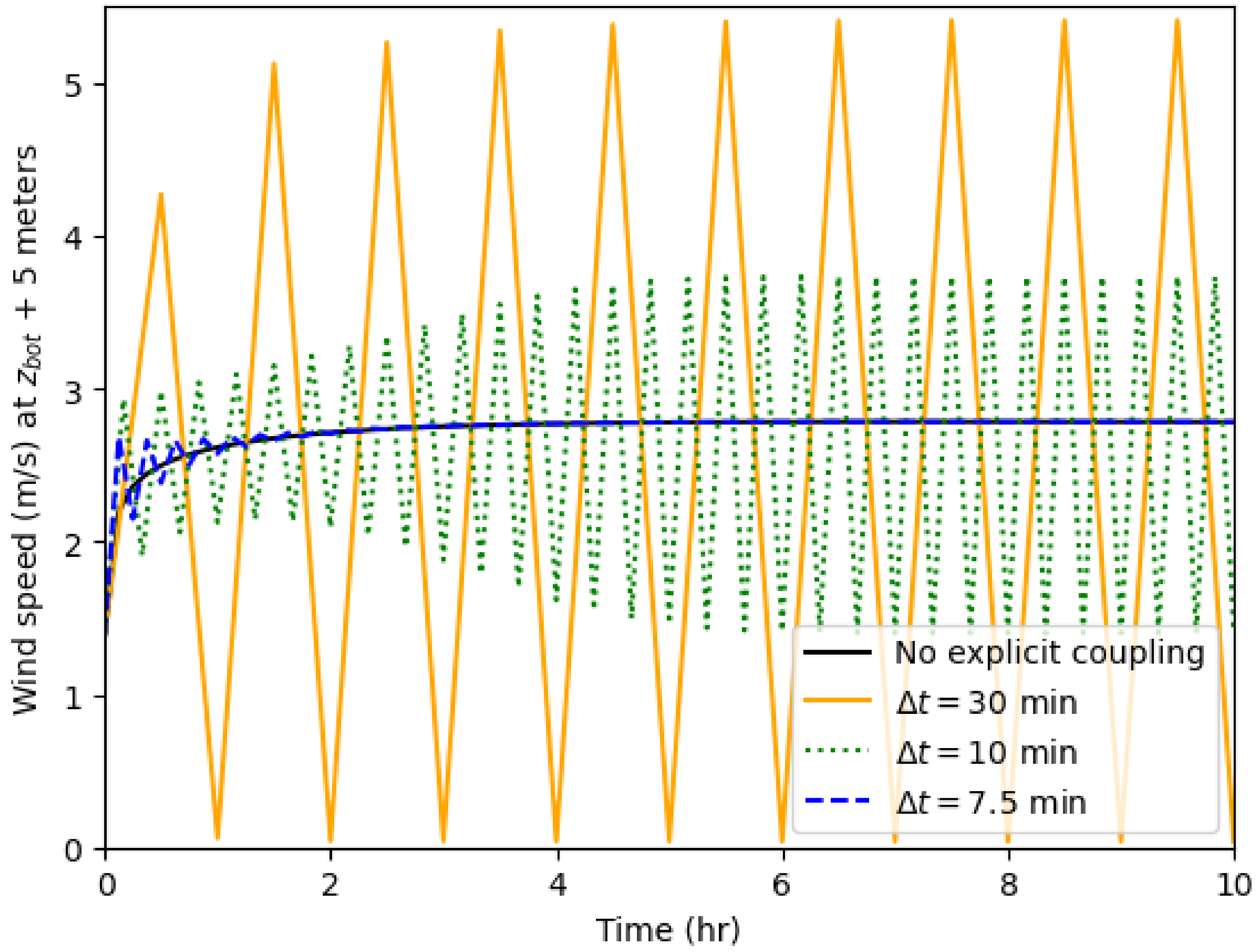
$$\Delta t < \eta \left[\mathrm{erf}^{-1} \left(\frac{\sqrt{K\rho}}{\sqrt{\eta} \left(\frac{d|\tau|}{d|s|} \right)} \right) \right]^2$$

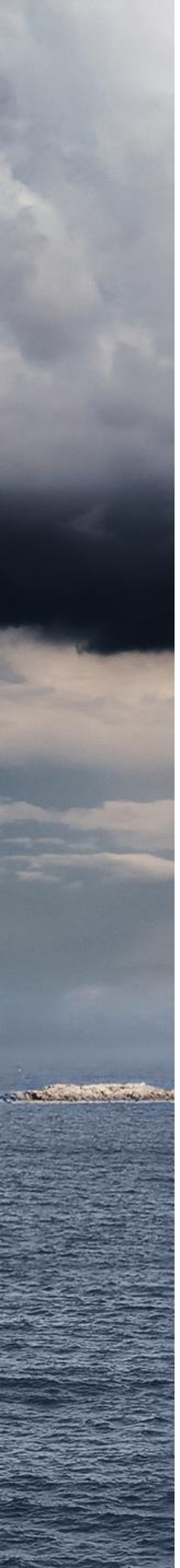
  - Valid at equator; if $f \neq 0$ the expression is complicated, involves an infinite series.
- Since this is a little unwieldy to evaluate, there is a simpler, weaker bound using the friction velocity u_*:

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

Reproducing oscillatory behavior

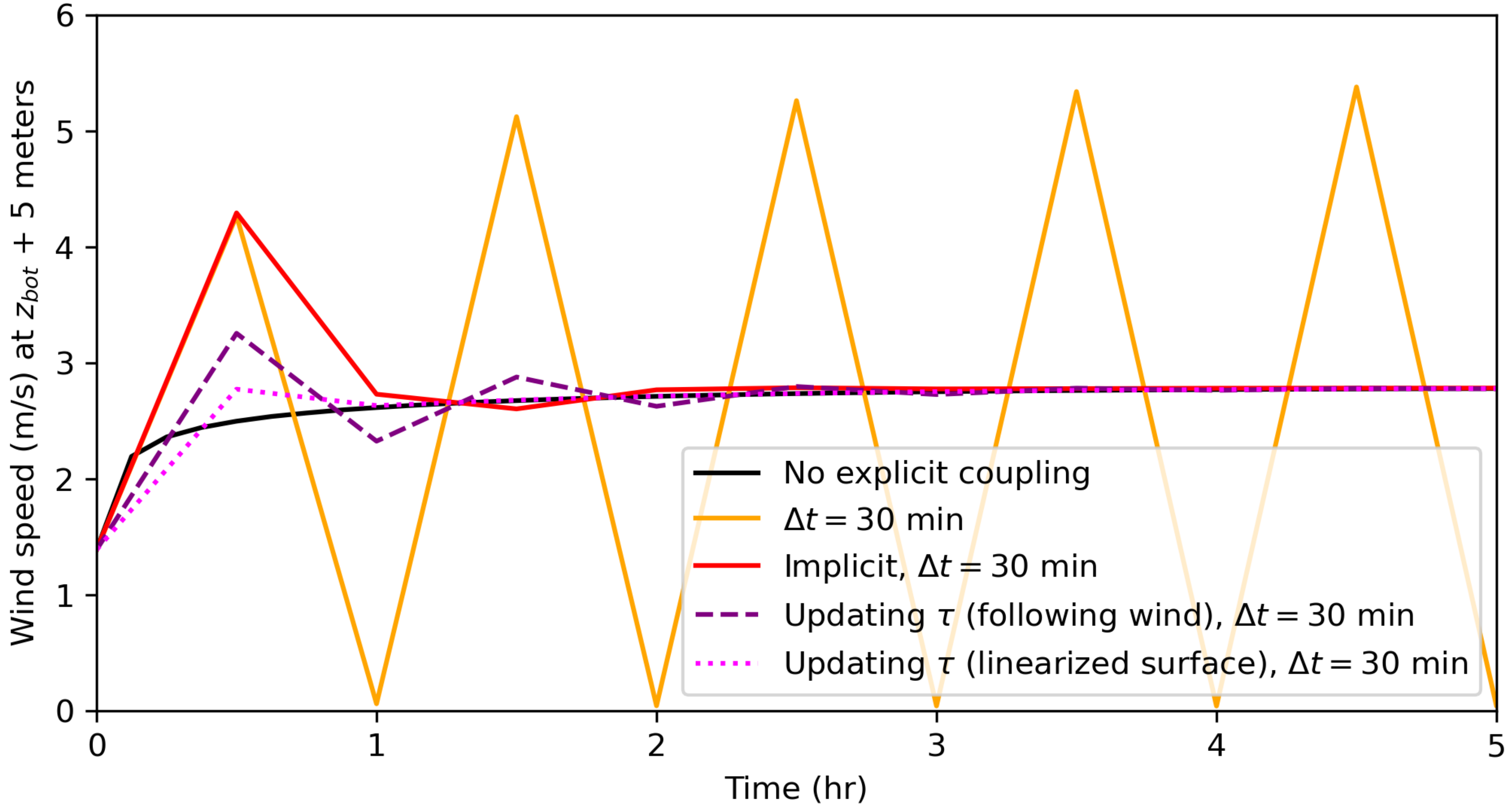
- Numerically, we can also reproduce the oscillations.
- 30 min time step requires limiter to avoid blowing up (the limiter prevents the wind direction from being reversed by friction).
- This gives us a test problem to try different numerical methods on.

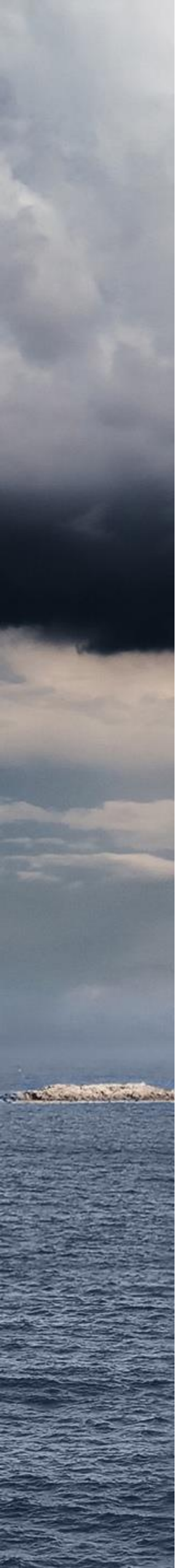




Testing different methods

- Several modifications are effective, including modifying the surface stress in the atmosphere (approach now used in CAM), and using implicit flux coupling.

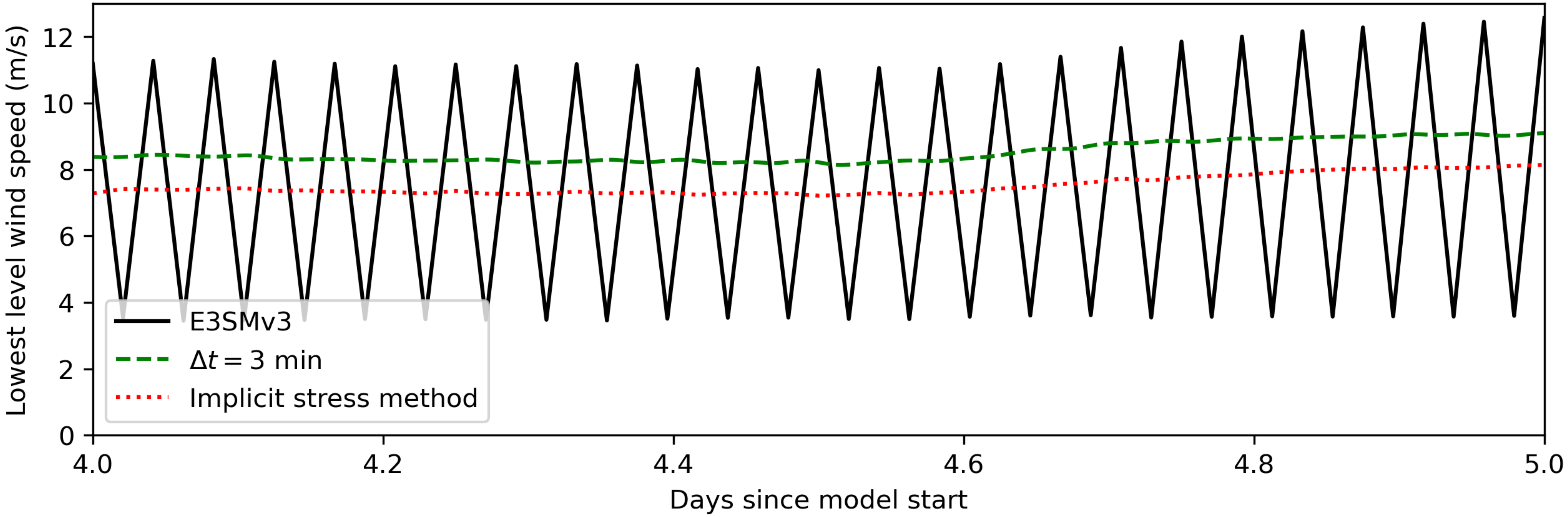




Implicit flux coupling implementation

- Traditional implicit flux coupling requires a specific model design:
  - All components use same time step size.
  - All components must use compatible semi-implicit vertical diffusion solvers.
  - Atmosphere must couple to other components in the middle of the PBL scheme.
  - Tricky to understand what happens with multiple models on different grids.
- To get around this, a novel predictor-corrector design:
  - Atmosphere generates a measure of the sensitivity of boundary layer winds to surface drag, and passes this to the coupler.
  - For a given surface stress, the land (or other) model can estimate the winds at the next time step.
  - For the implicit method, we want to solve a nonlinear equation to find the stress consistent with the next time step wind; we piggyback off the iterative solver used for Monin-Obukhov calculations to do this.
  - The atmosphere is given this stress, then actually advances its own state.

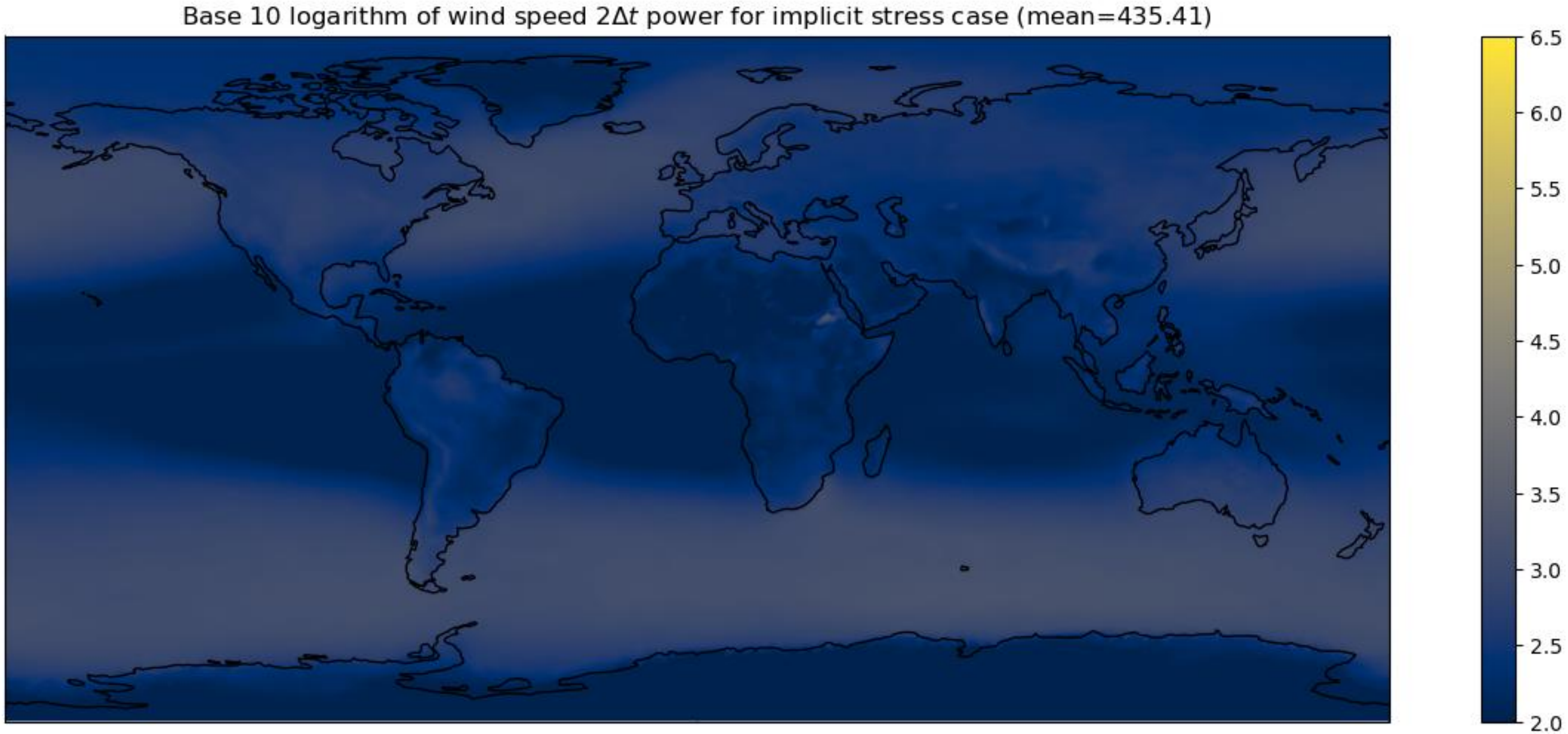
Implicit flux coupling removes the oscillations



- With implicit stress method, oscillations are removed without changing mean wind.
- Note: Results rarely match those with a 3 min time step, but qualitatively similar, and with no clear systematic difference (this example happens to have higher winds at finer timestep).

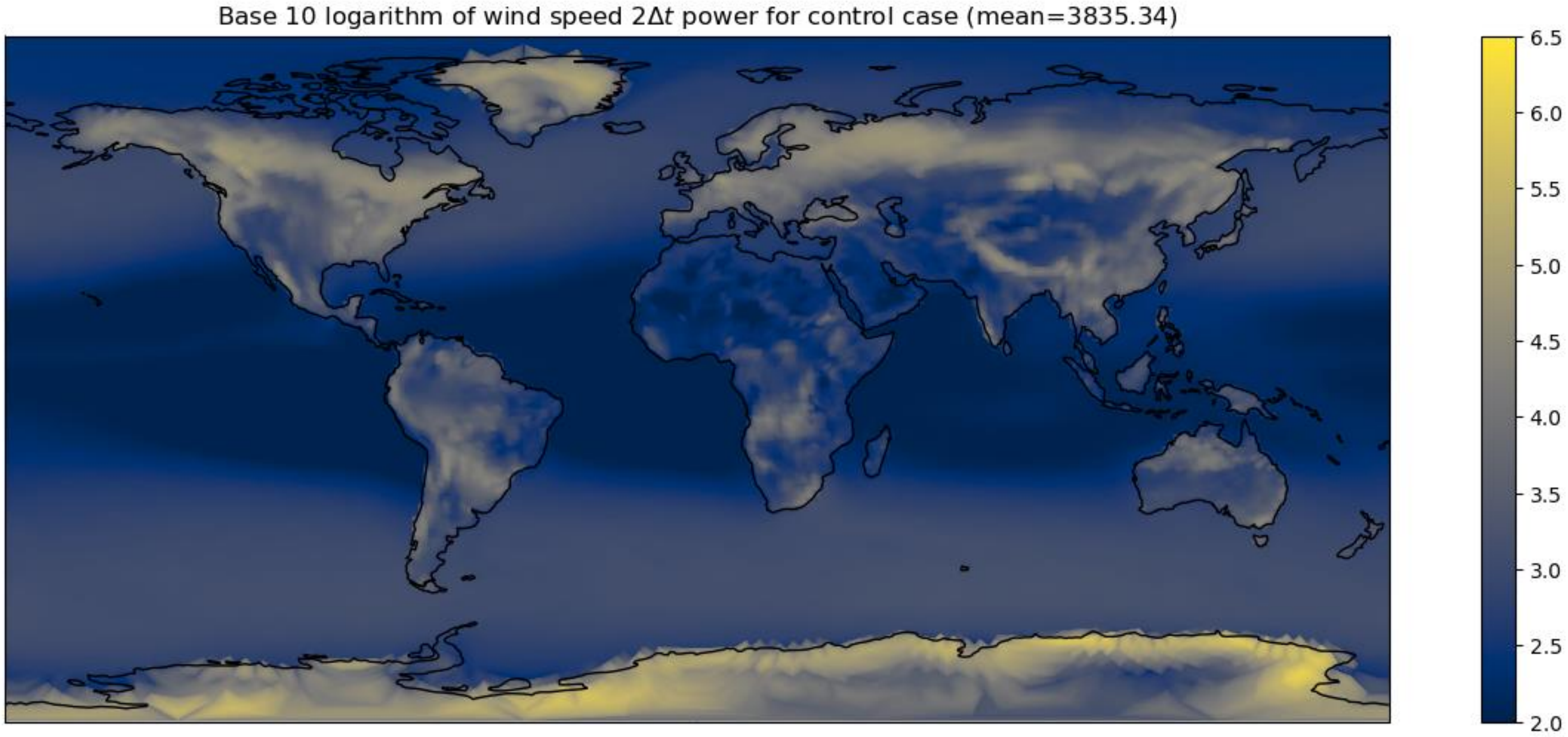
Implicit flux coupling removes the oscillations

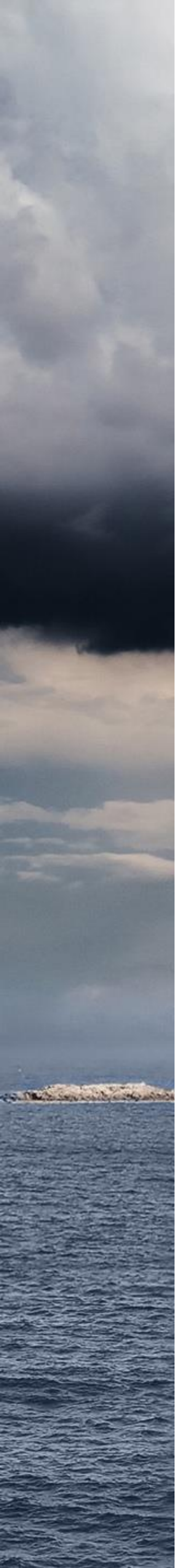
- Results for implicit flux coupling case.



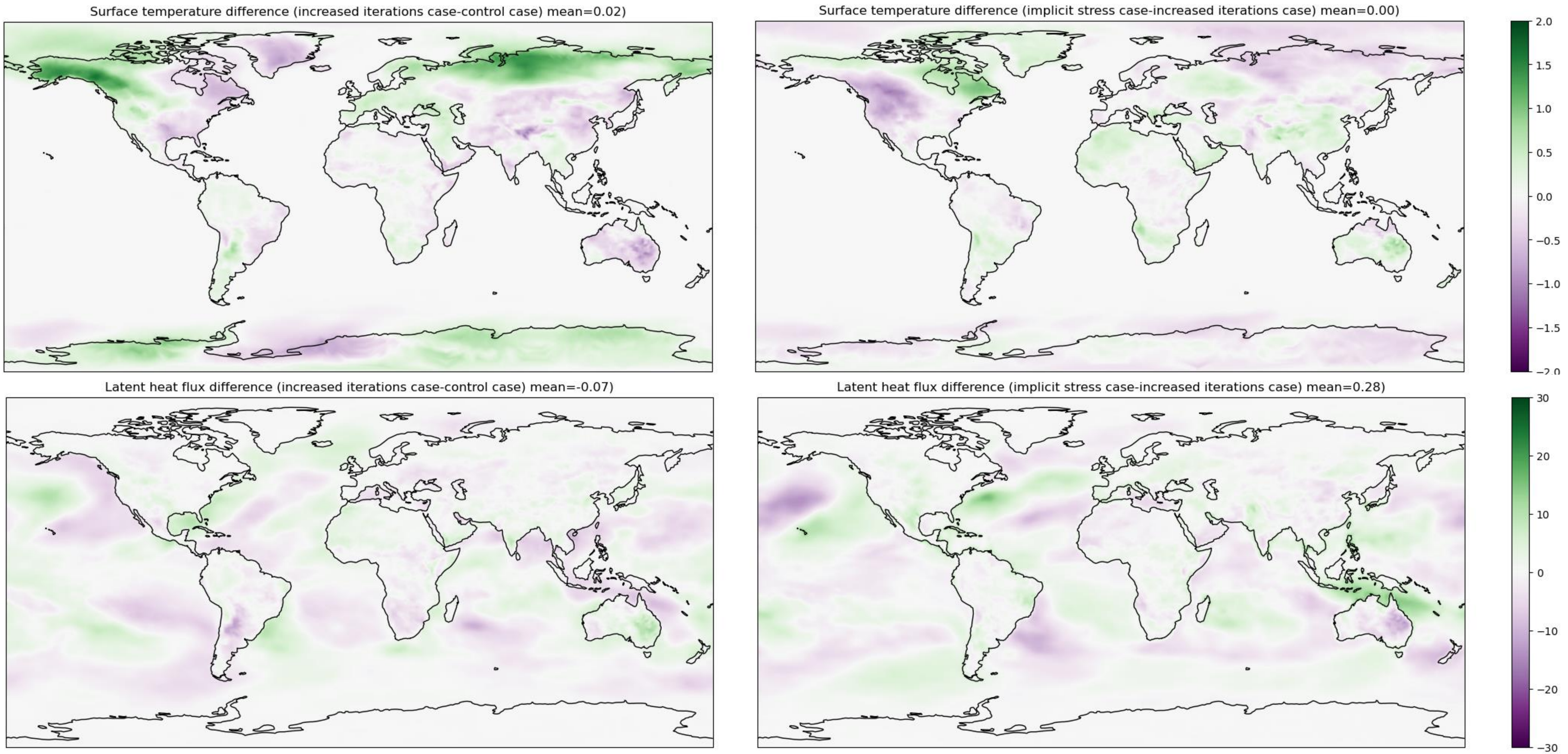
Implicit flux coupling removes the oscillations

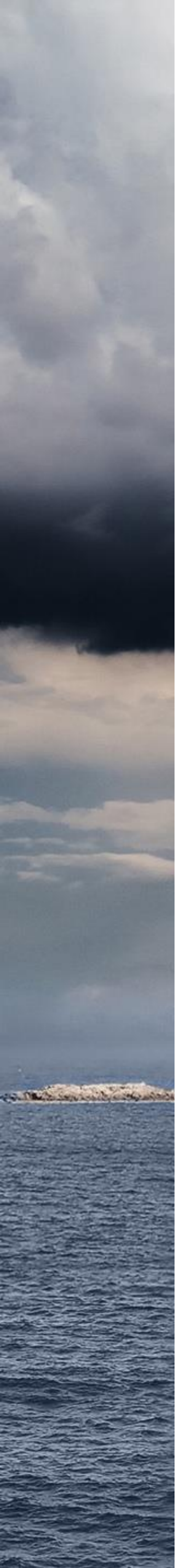
- Results for control case again.





Climate impact small compared with increasing the number of iterations in land+ocean M-O calculations



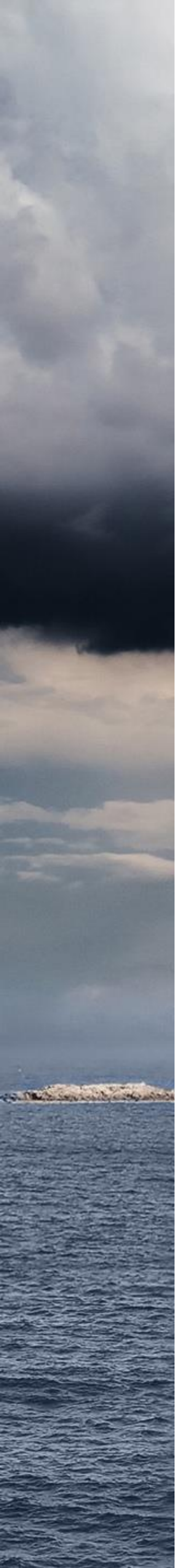


Downsides and alternatives

- This version of implicit flux coupling requires significant CLUBB modifications to solve for momentum fluxes twice, to find the sensitivity parameter.
  - Slight added expense; 1-3% extra atmosphere run time.
  - Extra complexity, could be a bit tedious to port to SHOC.
- Experimenting with a different sensitivity parameter calculation using elements of the band-diagonal matrix used in the vertical diffusion solver.
  - Might be less accurate, but also might be more appealing due to its simplicity.
- The band-diagonal implementation shows promise now, but the initial implementations failed due to the next issue…

The other implicit surface momentum flux calculation

- The implicit flux coupling method discussed before is about **calculation** of fluxes passed between components.
- However, CLUBB's **`l_imp_sfc_momentum_flux`** option is used in E3SM to **apply** the calculated momentum flux to the atmospheric state.
  - If this option is disabled, EAM crashes; for me this took 10 simulated months.
  - SHOC uses a similar method, so this is not v3-specific.
- This option increases model stability and is currently needed, but causes problems for conservation of momentum at the model boundary.



`l_imp_sfc_momentum_flux` basics

- This option starts with the observation that

$$\rho u_*^2 = \sqrt{\tau_x^2 + \tau_y^2}$$

  - Here ρ is atmospheric density, u_* is friction velocity, and $\tau = (\tau_x, \tau_y)$ is the surface stress.

- Under the assumption that τ points in the opposite direction from the wind (u, v), we can infer that:

$$\tau_x = -\left[\frac{\rho u_*^2}{\sqrt{u^2 + v^2}}\right] u, \qquad \tau_y = -\left[\frac{\rho u_*^2}{\sqrt{u^2 + v^2}}\right] v$$

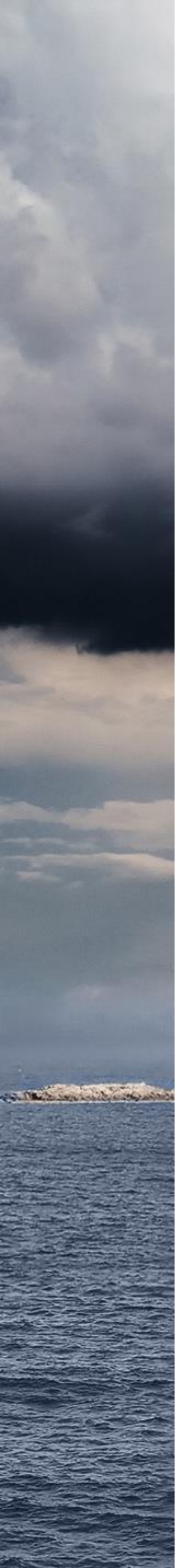
- The `l_imp_sfc_momentum_flux` option leverages this by computing the value in the brackets, and adding it to an element of the matrix in the left-hand side (implicit part) of the equation in its Crank-Nicolson solver.
- This element of the matrix is multiplied by the velocity, recovering the stress.

`l_imp_sfc_momentum_flux` problems

- First, the implementation mixes (u, v) values from different time levels (i.e. next time step values in the numerator, and current time step values in the denominator), so this equation results in a different (often smaller) stress.
  - Arguably this is both bug and feature; this is why the method is more stable.
- Second, this option does not seem to account for the sequential splitting that exists in the host model.
  - By the time CLUBB(/SHOC) runs, the wind is not necessarily the same value as was originally used to calculate the surface stress.
  - Therefore, the assumption that the stress points in the opposite direction from the current wind is also incorrect.
- Third, this option assumes that motion of the surface is negligible compared with that of the atmosphere.
  - But if an ocean current is comparable in speed to the wind, then the assumption about the direction of the stress is again incorrect.

What can be done?

1. Doing nothing is an option.
   - The momentum conservation violation is straightforward to measure, but we don't prioritize conservation of momentum in the same way as energy or mass.
   - How to evaluate whether this is a serious issue?
2. Try to improve the stability of the model in some other way, and move the surface flux term back to the right-hand (explicit) side of the equation.
   - Make the boundary layer more diffusive in some cases? Substep this calculation?
3. Modify this method to account for movement of ocean/sea-ice.
   - I.e. replace (u, v) with $\left(u - u_{srf}, v - v_{srf}\right)$, where $\left(u_{srf}, v_{srf}\right)$ is mean ocean/sea-ice speed.
4. Measure the momentum conservation violation, and implement a fixer
   - Send back to the more massive ocean/sea-ice/land component to absorb it?



Conclusions

- E3SMv3 is subject to spurious high-frequency oscillations in near-surface winds (and fluxes).
- These are due to a numerical instability arising from the use of explicit flux coupling at a long (30 min) time step, and this instability can be studied in a simplified model.
- A predictor-corrector implicit flux coupling method can remove these oscillations without large changes in model climate.
- Momentum conservation is trickier; CLUBB/SHOC has an internal “implicit” method for applying the calculated fluxes that is non-momentum-conserving.

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Thank you