Investigating sensitivity to dust in tropical cyclone formation using the GEOS-5 adjoint model

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Motivation

How much (if at all) does Saharan dust affect the development of tropical cyclones?

Tropical cyclones need heat and moisture, but:
- Dust can absorb and reflect incoming radiation, cooling the atmosphere below
- As dry dusty air from the SAL is entrained it can reduce the available energy

On the other hand:
- Dusty layers can be warm due to absorption
- Dust can increase condensation through micro-physics

Here we examine the radiative effects using the GEOS-5 adjoint so effects of dust can be examined explicitly.
Outline

▶ Motivation

▶ Model/experiment setup

▶ Example 1: Circulation metric

▶ Example 2: Surface pressure metric
Adjoint setup

Use the GEOS-5 adjoint to propagate sensitivity,

\[ \frac{\partial J}{\partial x} = M^\top \frac{\partial J}{\partial y} \]

The cost function \( J \) is a metric relevant to the forming TC:

- Mean circulation
- Mean energy (KE/PE/Moist)
- Surface pressure

Build up understanding using different metrics, set to different areas and with different combinations of model layers.
Necessary Modifications

- Linearize the longwave and shortwave radiation schemes
- Linearize the Mie table lookups (No RH for dust)
- Include dust variables (5 bins from 0.1\(\mu\)m to 10\(\mu\)m)
- Linearized third order advection scheme
- Linearization of GOCART (10m winds, emissions, settling, dry deposition, no wet removal or scavenging)
- Ability to perturb aerosols in nonlinear model
Hurricane Helene

- 2006 season had an intense dust outbreak
- Results are shown for Hurricane Helene, TC on 12 Sep
- Forecasts produced with a 25km horizontal resolution
- TLM/adjoint is run at 50km (and 25km)
- 72h forecasts, initialized on September 9th at 21z
Dust mixing ratio at 850hPa / Sea Level Pressure

12-Sep-2006 1200UTC
Potential Vorticity at 850hPa

Example adjoint input regions ($J$)
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Sensitivity to Dust (850hPa, 48 hours before)
Comparison with sensitivity to temperature
Moist physics
Run with linearized convection and single-moment microphysics.

Specific humidity | 10–Sep–2006 1200UTC

Specific humidity (sens) | 10–Sep–2006 1200UTC

Dust − BIN1 | 10–Sep–2006 1200UTC

Dust − BIN1 (sens) | 10–Sep–2006 1200UTC
Perturbation Construction

Now wish to construct and test some perturbations to:

- Understand the extent of the adjoint validity
- See what effects they have on the developing storm
- Understand how much dust can alter temperature

There is a lot of flexibility when constructing a tracer perturbation.

1. Take just the negative or positive parts of the sensitivity
2. Weight the sensitivity by the mass of the layer
3. Adjust at each level to reflect some realistic values of dust for that layer (for this case around 20% change)
Positive Dust Perturbation (850hPa PV difference)
Negative Dust Perturbation (850hPa PV difference)
General observations

• Largest sensitivity occurs over Northern Mali/Algeria
• Sensitivity structure is similar at other levels (up to around 500hPa)
• Sensitivity is largest in bin 1 (0.1µm to 1µm)
• Sensitivity to dust is smaller than other fields (but uncertainty is likely higher)
• ‘Positive’ sensitivity is more widespread than ‘negative’ sensitivity
• Mostly dry dynamics at this stage of Helene’s life cycle
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Surface pressure sensitivity to dust 550hPa

![Map showing surface pressure sensitivity to dust 550hPa with contours indicating sensitivity levels and geographic coordinates.](image-url)
Warming/cooling below

Can we create a warming/cooling in sensitive region by perturbing dust above?

- Initialize the adjoint with surface pressure metric over larger box
- Generate initial perturbations around level 55 ($\approx 700\text{hPa}$)
- Very large $> 100\%$ positive perturbation
Temperature perturbation lowest level

Temperature | 10−Sep−2006 1400UTC

Temperature | 10−Sep−2006 1800UTC

Temperature perturbation

Longitude (°)

Latitude (°)

Temperature perturbation

Longitude (°)

Latitude (°)
Impact on Surface Pressure TLM vs NLM

Result of large perturbations of dust at all levels on surface pressure.

**TLM**
- Mean pressure reduction in the box: 0.28hPa
- Max pressure reduction in the box: 0.40hPa

**NLM**
- Mean pressure reduction in the box: 0.04hPa
- Max pressure reduction in the box: 1.39hPa
Nonlinear Sea Level Pressure

Unperturbed

Longitude (°)
Latitude (°)
-40 -30 -20 -10 0
5 10 15 20 25 30

Perturbed

Longitude (°)
Latitude (°)
-40 -30 -20 -10 0
5 10 15 20 25 30

Difference

Longitude (°)
Latitude (°)
-40 -30 -20 -10 0
5 10 15 20 25 30

(hPa)
-1 -0.5 0 0.5 1
Conclusions

- The adjoint is shown to be a useful tool for examining sensitivity to dust (aerosols) through radiation
- 48 hours is about the limit for dry GEOS-5 (shorter for moist)
- Dominant sensitivity is direct warming/cooling
- Secondary effects hard to study in this context
- ‘Positive’ sensitivity dominates
- Increasing dust shown to increase strength and vice versa
- Sensitivity smaller than for other fields
- Adjoint may under-predict sensitivity
- Sensitivity to dust for region looked at is over Sahara and inland
Future work?

- Downstream (limited by physics)
- Look at impact of observations in sensitive region