How waviness in the circulation changes surface ozone: A viewpoint using local finite-amplitude wave activity

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Atmospheric Waviness: The jet-stream on two days

**Wavy Jet Stream**: Associated with atmospheric blocking, temperature and precipitation extremes.

**Zonal Jet Stream**: Usually associated with quieter weather
Objective Metric to Characterize Atmospheric Waviness: Wave Activity

Consider a potential vorticity contour $Q$ in upper troposphere

- Find the equivalent latitude (where red and blue shading are of equal area)
- Local Wave Activity at longitude and latitude ($\lambda_o, \phi_o$) is equal to the perturbation potential vorticity times the distance displaced from the equivalent latitude
- The local wave activity is split into an anticyclonic (red) and cyclonic portion (blue)

-Zonally averaged finite-amplitude wave activity (Nakamura and Zhu, 2010) mathematically relates large scale wave dynamics to the atmospheric circulation

-The local wave activity LWA is defined locally at a particular longitude and latitude. It can be used to differentiate longitudinally isolated events and to characterize local and regional weather. A diagnosis of LWA also provides a metric for the occurrence of blocking events, events associated with anomalous or extreme mid-latitude weather events such as heat waves.
Objectives

• How does surface ozone respond to the waviness of the flow as diagnosed by Local Wave Activity?
• How do meteorological biases in the CESM as evident by biases in wave activity impact the ozone distribution?
• How does Local Wave Activity change in a future climate over the US?
• How do these changes in future waviness impact future ozone distributions?
Why use Local Wave Activity (LWA) to diagnose surface ozone?

- The use of LWA to diagnose the waviness of the circulation emphasizes zonally asymmetries with associated regional impacts.

- LWA potentially makes a good candidate for relating surface ozone to characteristics of the general circulation as its part of a larger theoretical framework.

- The impact of climate change on large scale features of the circulation as generally diagnosed with wave activity is likely more robust than that on smaller scales.
JJA Anticyclonic Local Wave Activity ERA-Interim (JJA, 1994-2013) and GCM 2000 (CESM1, 20 years, constant present day reactive emissions), Geopotential Height (lines)

- Analysis based on Anticyclonic Local Wave Activity (by far the dominant part over the US during JJA)
- Use 500 hPa geopotential height contours to diagnose LWA instead of potential vorticity to simplify the analysis

Sun et al., 2019, ACPD
Maximum Covariance Analysis Between Surface Ozone and Wave Activity

Maximum Covariance Analysis (MCA) (Wilks, 2011) finds the patterns in two spatially and temporally varying fields that explains the maximum fraction of covariance between them.
Maximum Covariance Analysis

- Observations: Castnet Ozone and ERA-Interim meteorology (JJA, 1994-2013)
- GCM2000: Online CESM constant emissions (JJA, 20 years) sampled at CASTNET stations

Interpretation
- 1st mode interpreted as impact of low pressure systems crossing US
- 2nd mode interpreted as westward expansion of the North Atlantic subtropical anticyclone

- Poor simulation of 2\textsuperscript{nd} mode consistent with CESM biases in simulation of the North Atlantic Anticyclone
- Maybe consistent with the poor simulation of the temperature-ozone correlation in the northeastern U.S (Phalitnonkiat et al., 2018).

Observed and Modeled Local Wave Activity (shade) and Ozone at CASTNET Stations (Shaded Diamonds)  
Sun et al., 2019, ACPD
JJA 20-year average at 850 hpa for ERA interim (shade), GCM2000 simulation (black contour) and GCM2100 simulation (grey contour).

South Atlantic Anticyclone Displaced west of its climatological position in CESM.

This likely to impact variability due to westward expansion of the cyclone.

Little westward movement of the anticyclone in the future (despite the fact that a westward shift of this anticyclone is rather robust feature of future climate simulations).
Relationship between ozone at any point and wave activity within the study region through a series of regression relationships:

- shading: simulated relationship in GCM2000
- diamonds: relationship from observations at CASTNET sites

Sun et al., 2019, ACPD
JJA Wave Activity Bias:
- GCM2000 (20 years) minus ERA Interim (‘94–’13)

JJA Ozone Differences due to Wave Activity Bias
- Shades: Sensitivity from Simulation
- Diamonds: Sensitivity from Measurements
  - Approximately a 4-8 ppb + ozone bias in the interior southeastern US and a
  - Approximately a 4 ppb low ozone bias in the northeast

Sun et al., 2019, ACPD
Future Change in Geopotential Height and Anticyclonic Wave Local Wave Activity (JJA 2100 minus 2000)

Sun et al., 2019, ACPD
Future Change in Anticyclonic Wave Local Wave Activity (JJA 2100 minus 2000) for Four Simulations

Large Positive Anomaly in the Western US in all simulations!

Note the similarities with the present day bias (GCM2000-ERA INTERIM)

Sun et al., 2019, ACPD
Projected Change in Ozone (JJA 2100 minus 2000) for Four Simulations Due to Change in Local Wave Activity

- Regional ozone changes attributed to the future changes in ALWA range from approximately -2.5 ppb to 2.5 ppb
- Increases in the SE, generally decreases in the NE

JJA Ozone Differences due to Wave Activity Bias
- Shades: Sensitivity from Simulation
- Diamonds: Sensitivity from Measurements

Sun et al., 2019, ACPD
• Future Ozone Change is Positive due to changes in climate
• In some locations O3 change due to circulation changes oppose those from climate
• In many locations outside the NE US changes in circulation are the predominant cause of ozone change
Conclusions

• Local Wave Activity used to diagnose CESM1 circulation biases during JJA
  • Wave activity biases result in O3 biases -4 - + 8 ppb over US
  • Incorrect simulation of O3 variability over the NE US attributed to bias in simulation of North Atlantic Anticyclone

• Robust Large Scale future change in LWA occur overs the W. US. during JJA
  • Future change similar to present-day simulation biases.
  • Results in JJA future O3 change -2.5 – 2.5 ppb due to circulation changes
    • Changes are much larger when compared against present day reanalysis
    • Explains future ozone change in some locations, but overall changes are not due to changes in circulation
Sensitivity of O3 at selected gridpoints to waveactivity (ppb/m2)

Sensitivity (JJA) determined from linear regression of ozone at a particular point to wave activity at all points within domain

Overall impact of wave activity on ozone determined by projection of wave activity on the sensitivity

Sun et al., 2019, ACPD