Recent Trends in Methane: A Spatio-Temporal Analysis

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The Methane Problem

• Methane is the second most important greenhouse gas (after carbon dioxide) resulting from human activities.
• Humans are responsible for a little more than half of the emission of methane.
• Once in the atmosphere, methane absorbs terrestrial infrared radiation that would otherwise escape to outer space.
• Remains in the atmosphere for approximately 9-15 years and is over 20 times more effective in trapping heat in the atmosphere than carbon dioxide.
Methane’s Harms

- Recent studies have shown that methane is on the rise
- Scientists have been finding large amounts of methane being released from methane “chimneys” from beneath the Arctic seabed
- It has been thought that the permafrost layer acts as sort of a lid to trap the subsea methane from being released into the atmosphere
- That is why scientists are now concerned about a possible positive feedback loop
- The melting of the permafrost layer which releases methane into the atmosphere, which then in turn causes the earth to warm and more of the permafrost layer to melt, which then causes yet even more methane to be released into the atmosphere.
- Such a feedback loop would greatly exacerbate the effects of global warming, and its results could be catastrophic.
• Graphic courtesy of: http://sitemaker.umich.edu/section2_group1/arctic_issues__permafrost
Methane’s harms (cont.)

• Major contributor to global warming
• The increase of global temperatures causes the world’s glaciers to melt, which is a major threat to the populations that depend on these glaciers for fresh water
• It will cause a rise in global sea levels, which will cause flooding in certain parts of the globe
• It will desalinize the ocean
• Temperatures will rise, more extreme weather conditions such as hurricanes, tornadoes, and wildfires, increased probability and intensity of droughts and heat waves, and the spread of disease
Is methane increasing, decreasing, or staying the same?

• To answer this question, we need data. Through the generous help of 2 resources (credited on our cover submission), we acquired monthly airborne methane concentration averages across 23 sites for years 1983-2007.
Long Term Trend

• The points representing years 1300-1950 are icecore measurements, blue from the Antarctic, green (slightly above the blue, mostly), from near the Arctic. The two high values to the far right, averaged values from the previously mentioned data (included to provide an overall sense of increase).

• Atmospheric methane has been exponentially increasing since around the mid 1700s, which coincides with the Industrial Revolution.
More Recent Trend

- More recent methane concentrations by hemisphere (top), and more finely, by latitude (bottom):
- Methane concentrations are higher in the northern hemisphere than they are in the southern hemisphere; this is mainly due to the fact that the northern hemisphere has larger sources of methane.
- We can also see that methane concentrations vary seasonally, due to atmospheric chemistry: the removal of methane by the hydroxyl radical, causing a minimum in the late summer.
Spacial Prediction: Kriging

• To begin our analysis, we wish to describe the spacial distribution of methane across the globe.
• In order to describe the entirety of Earth's surface, it is necessary to use our data from fixed sites to predict concentrations at an arbitrary location.
• We create a raster wireframe to represent predicted values over the whole of the globe.
• There are a number of statistical methods available for this:
  • “spacial interpolation”, in which a value for an arbitrary location is predicted as a function of transforms of the supporting space.
  • Another method is kriging, where values at arbitrary locations are predicted using the covariance structure of the observed data.

Graphic courtesy of:
The essence of kriging is the covariogram (or analogously the variogram), a function that maps pairwise distance between locations and the response covariance (or variance of the difference of responses).

Two observations of some terrestrial phenomenon acting over space will likely be correlated more strongly the closer together they are.

With such a function, one can then predict an arbitrary location by estimating covariances using the $n \times n$ distance matrix whose elements are the pairwise distances between the known $n$ locations, and the $n \times 1$ vector of distances between the known locations and the new, unmonitored location.
Space-Time Prediction

• In order to understand spacial and temporal trends of atmospheric methane we employed an extension of kriging.
• In the paper, we briefly introduce kriging, here we provide more detail about our space time algorithm.
• Generally, the problem is viewed as a least squares prediction problem. An unseen value at time $t$ at an arbitrary location is assumed a linear function of predictors and lag estimates.
• The lag estimates are generated using covariogram kriging, and the “primary” least squares parameter is progressively estimated by “jackknife.”
"grand" estimate at site $j$
\[ \hat{z}^{(k)}(s_j) = z_{t-k+1}(-j) w_t^{(k)}(s_j) \]
\[ o \hat{z}_t(s_j) = (x_{t;j}, \hat{z}_t(s_j)) b_{t-1} \]

primary least squares parameter

covariogram
\[ C_{zzt-k}(-j, -j) = C_t(D_{ss}(-j, -j), \theta_{t-k}) + \lambda^{(k)} I \]
\[ c_{zz}^{(k)}(-j, s_j) = C_t(d_{ss}(-j, s_j), \theta_t) \]
\[ w_t^{(k)}(-j, s_j) = C_{zzt-k}(-j, -j)^{-1} c_{zz}^{(k)}(-j, s_j) \]

least squares regularizer
\[ \hat{z}_t^{(k)}(s_j) = z_{t-k+1}(-j) w_t^{(k)}(-j, s_j) \]
\[ L_{xxt} = L_{xxt-1} + g_t \cdot \left( \Xi_t^T \Xi_t - L_{xxt-1} + \gamma I \right) \]
\[ l_{xxt} = l_{xxt-1} + g_t \cdot \left( \Xi_t^T z_t - l_{xxt-1} \right) \]
\[ b_t = L_{xxt}^{-1} l_{xxt} \]

update gain
\[ g_t = \frac{g_{t-1} + \rho_t}{g_{t-1} + \rho_t + 1} \]

"grand" estimate at arbitrary site, $s$
\[ \hat{z}_t^{(k)}(s) = z_{t-k+1} \left( C_{zzt-k}^{(k)} -1 \right) c_{zzt}^{(k)} \]
\[ o \hat{z}_t(s) = (x_{t;s}, \hat{z}_t) b_t \]
Spacio-Temporal Prediction

Please click on image to begin movie.
\[ \mathbf{X}_t = \begin{pmatrix}
\mathbf{x}_{t;1} & \hat{z}_t^{(1)}(s_1) & \hat{z}_t^{(2)}(s_1) & \cdots & \hat{z}_t^{(d)}(s_1) \\
\mathbf{x}_{t;2} & \hat{z}_t^{(1)}(s_2) & \hat{z}_t^{(2)}(s_2) & \cdots & \hat{z}_t^{(d)}(s_2) \\
\ddots & \ddots & \ddots & \ddots & \ddots \\
\mathbf{x}_{t;n} & \hat{z}_t^{(1)}(s_n) & \hat{z}_t^{(2)}(s_n) & \cdots & \hat{z}_t^{(d)}(s_n)
\end{pmatrix} \]

\[ \hat{\mathbf{Z}}_t(s_j) = \begin{pmatrix}
\hat{z}_t^{(1)}(s_j), \hat{z}_t^{(2)}(s_j), \ldots, \hat{z}_t^{(d)}(s_j)
\end{pmatrix} \]

<table>
<thead>
<tr>
<th>symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbf{D}_{ss} )</td>
<td>Distance matrix</td>
</tr>
<tr>
<td>( \mathbf{d}_{ss}(s_x) )</td>
<td>Distance vector; distances to site ( s_x )</td>
</tr>
<tr>
<td>( \mathbf{d}_{ss}(-j, s_x))</td>
<td>Distance vector; distances, site ( j ) removed, to site ( s_x )</td>
</tr>
<tr>
<td>( \mathbf{C}_{zz} )</td>
<td>Covariogrammed covariance Matrix</td>
</tr>
<tr>
<td>( \mathbf{c}_{zz}(s_x) )</td>
<td>Covariogrammed covariance vector (between known sites and ( s_x ) arbitrary)</td>
</tr>
</tbody>
</table>
Recent Trends

- To find out whether or not the increase from 2006 to 2007 in methane concentrations was significantly different than recent years, we conducted a paired t-test using methane data from 2003 to 2008 at 5 locations.
- H0: \( \mu_{2007} - \mu_{2008} = -4 \) for all months
- Ha: \( \mu_{2007} - \mu_{2008} < -4 \) for all months
- We use similar hypotheses for the years 2006-2007.
- There is sufficient evidence to conclude that not only have methane concentrations been increasing, but they are increasing by more than 4 ppb/year. If the rate of increase in methane concentrations was 4 ppb/year, then we could be looking at methane levels of about 2200 ppb in 100 years time. This could lead to a catastrophe.
Breaking News

• Until 2006, it seemed as if methane levels were leveling off
• However, recent studies have raised some concerns because they suggest that methane is on the rise again
• Methane levels rose sharply in 2007; this was thought to be an exception
• But according to the latest data available, methane levels had a significant rise again in 2008
• This was confirmed by our hypothesis test
• The long term potential cost of global warming, an issue fraught with personal and political disagreement, is enormous and ultimate understanding will require the full mosaic of science, statistics not the least of these. It offers a window to truth -- done conscientiously it is a messenger impartial to the message.